Cold nuclear matter effects on quarkonium production @ RHIC and LHC

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Work done in collaboration with
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EPJC61 (2009), PLB680 (2009), PRC81 (2010), NPA855 (2011)

Introduction: motivation

- A lot of work trying to understand **A+A** data (since $J/\psi \equiv$ QGP signal)

Quarkonium as a hint of deconfinement | QGP probe

- If we focalise on **p+A** data (where no QGP is possible)
  only cold nuclear matter (CNM) effects are in play here:
  shadowing and nuclear absorption

Quarkonium as a hint of coherence | nPDF probe

- In fact, the question is even more fundamental: **p+p** data
  we do not know the specific production kinematics at a partonic level:
  $(2 \rightarrow 2,3,4)$ vs $(2 \rightarrow 1)$

Quarkonium as a hint of QCD | QCD probe

Introduction : contents

Our goal:

To investigate the **CNM effects** and the impact of the specific **partonic production** kinematics

3 ingredients:

•J/ψ partonic production mechanism

•Shadowing

•Nuclear absorption

- Results on J/ψ production @ RHIC and LHC
- Extend our study to ϒ CNM effects : *fractional energy loss*

Quarkonium as a tool of COLD and HOT effects

- **cold effects:** **wo thermalisation NO QGP**

gluon shadowing
gribov shadowing

nuclear structure functions in nuclei $\neq$ superposition of constituents nucleons

NI@SPS, IMP@RHIC

nuclear absorption

multiple scattering of a pre-resonance c-cbar pair within the nucleons of the nucleus

IMP@SPS, RHIC?

CGC

percolation

parton saturation

non-lineal effects favoured by the high density of partons become important and lead to eventual saturation of the parton densities

non thermal
colour connection

partonic comovers

hadronic comovers

dissociation of the c-cbar pair with the dense medium produced in the collision
partonic or hadronic

suppression by a dense medium, not thermalized

Others: Cronin effect
EMC effect, energy loss

- **hot effects:** **w thermalisation QGP**

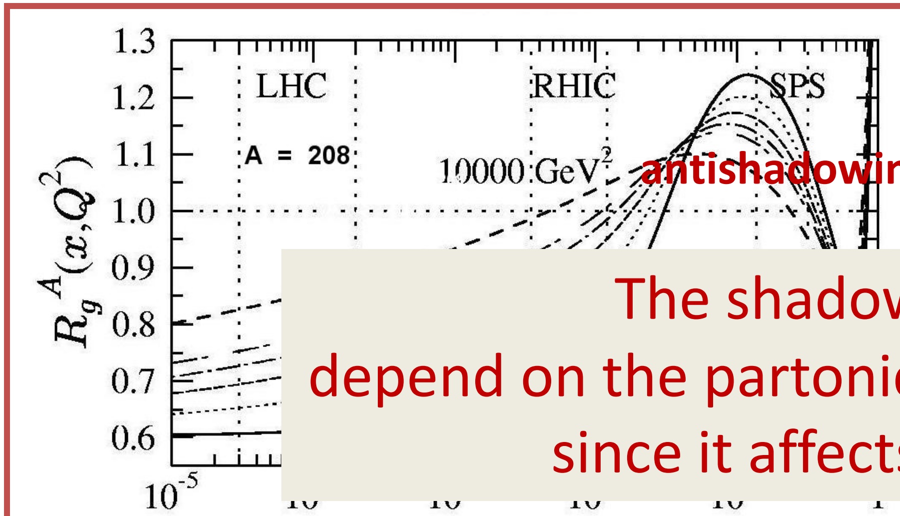
QGP | sequential suppression | recombination

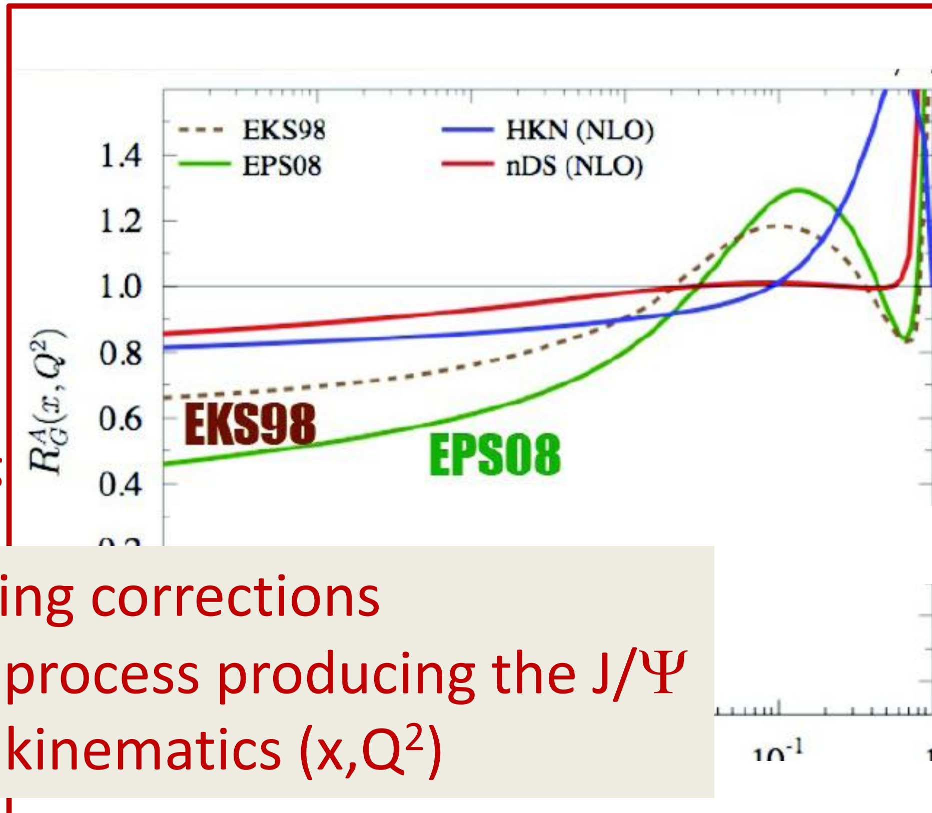
Shadowing: an initial cold nuclear matter effect

- Nuclear shadowing is an initial-state effect on the partons distributions
- Gluon distribution functions are modified by the nuclear environment
- PDFs in nuclei different from the superposition of PDFs of their nucleons

Shadowing effects increases with energy (1/x) and decrease with Q^2 (m_T)

$$R_i^A(x,\mu_f) = \frac{f_i^A(x,\mu_f)}{A f_i^{nucleon}(x,\mu_f)}\,, \quad f_i = q, \bar{q}, g$$





The shadowing corrections
depend on the partonic process producing the J/Ψ
since it affects kinematics (x,Q^2)

Nuclear absorption: a final **cold nuclear matter** effect

Particle spectrum altered by interactions with the nuclear matter they traverse
=> J/Ψ suppression due to final state interactions with spectator nucleons

- Usual parameterisation:
  (Glauber model)

$$\boxed{S_{abs} = \exp(-\rho\, \sigma_{abs}\, L)}$$

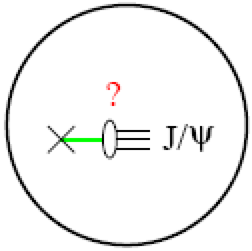
nuclear matter density   break-up cross section   path length

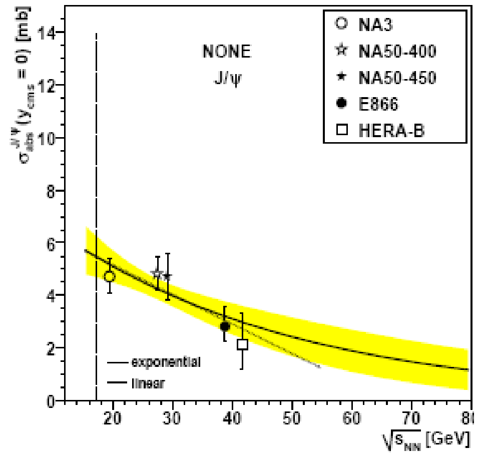
Energy dependence

- At low energy: the heavy system undergoes successive interactions with nucleons in its path and has to survive all of them => Strong nuclear absorption
- At high energy: the coherence length is large and the projectile interacts with the nucleus as a whole => Smaller nuclear absorption

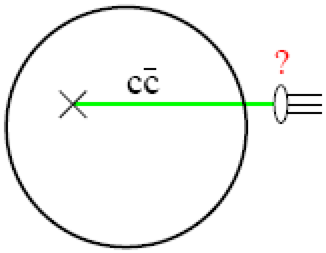
In terms of formation time:

Low energy: $t_f = \gamma(x_2)\,\tau_f \ll R$





High energy: $t_f = \gamma(x_2)\,\tau_f \gg R$



Rapidity dependence of nuclear absorption? σ_{abs} @ mid y < σ_{abs} @ forward y?

On the kinematics of J/ψ production: two approaches

- CNM -shadowing- effects depends on J/ψ kinematics (x,Q^2)
- J/ψ kinematics depends on the production mechanism =>

Investigating two production mechanisms (including p_T for the J/ψ):

g+g → J/ψ 2→1

- intrinsic scheme: the $\mathbf{p_T}$ of the J/ψ comes from initial partons
  - ❖Not relevant for, say, p_T>3 GeV
  - ❖Only applies if COM(LO, α_s^2) is the relevant production mechanism at low p_T

g+g → J/ψ+g, gg,ggg,… 2→2, 3, 4

- extrinsic scheme: the $\mathbf{p_T}$ of the J/ψ is balanced by the outgoing parton(s)
  - ❖COM, CSM (NLO, NNLO)

On the kinematics of J/ψ production: equations

If $\mathcal{F}_g^A(x,\vec{r},z,\mu_f)$ gives the distribution of a gluon of mom. fract. x at a position $\vec{r},z$ in a nucleus A, the differential cross-section reads :

$$\frac{d\sigma_{AB}}{dy\,dP_T\,d\vec{b}} =$$

$2 \to 1$ kinematics with instrinsic p_T

$$\int d\vec{r}_A\,dz_A\,dz_B$$
$$\times\ \mathcal{F}_g^A(x_1^0,\vec{r}_A,z_A,\mu_f)\mathcal{F}_g^B(x_2^0,\vec{r}_B,z_B,\mu_f)$$
$$\times\ \sigma_{gg}^{\text{Intr.}}(x_1^0,x_2^0)$$
$$\times\ S_A(\vec{r}_A,z_A)\,S_B(\vec{r}_B,z_B)$$

$$\boxed{x_{1,2} = \frac{m_T}{\sqrt{s_{NN}}}\exp(\pm y) \equiv x_{1,2}^0(y,P_T)}$$

$2 \to 2$ kinematics with extrinsic p_T

$$\int dx_1\,dx_2 \int d\vec{r}_A\,dz_A\,dz_B$$
$$\times\ \mathcal{F}_g^A(x_1,\vec{r}_A,z_A,\mu_f)\mathcal{F}_g^B(x_2,\vec{r}_B,z_B,\mu_f)$$
$$\times\ 2\hat{s}P_T\,\frac{d\sigma_{gg\to J/\psi+g}}{d\hat{t}}\,\delta(\hat{s}-\hat{t}-\hat{u}-M^2)$$
$$\times\ S_A(\vec{r},z_A)S_B(\vec{r}_B,z_B)$$

$$\boxed{\delta(..) \to x_2 = \frac{x_1 m_T\sqrt{s_{NN}}e^{-y} - M^2}{\sqrt{s_{NN}}(\sqrt{s_{NN}}x_1 - m_T e^{y})}}$$

shadowing

partonic cross section

nuclear absorption

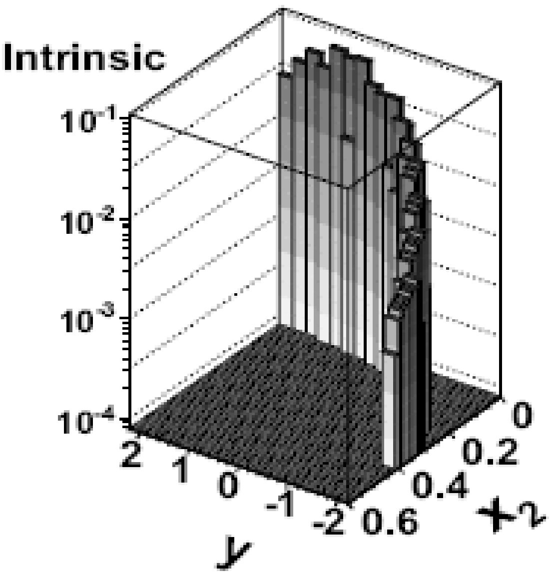
fit to data

kinematic variables

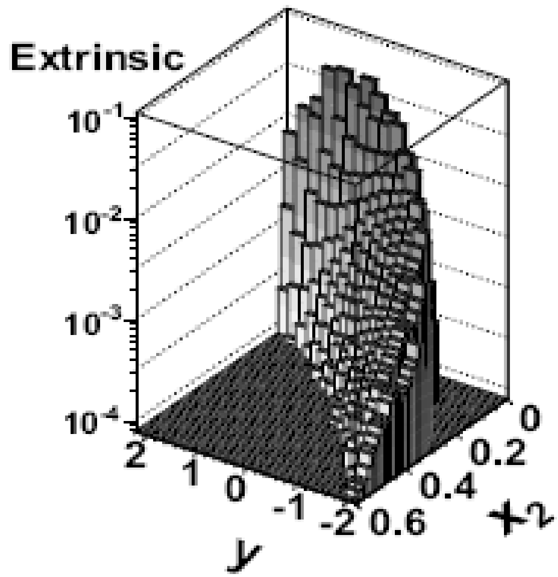
your preferred model

INTRINSIC (2→1) vs EXTRINSIC (2 → 2) kinematics

2 → 1



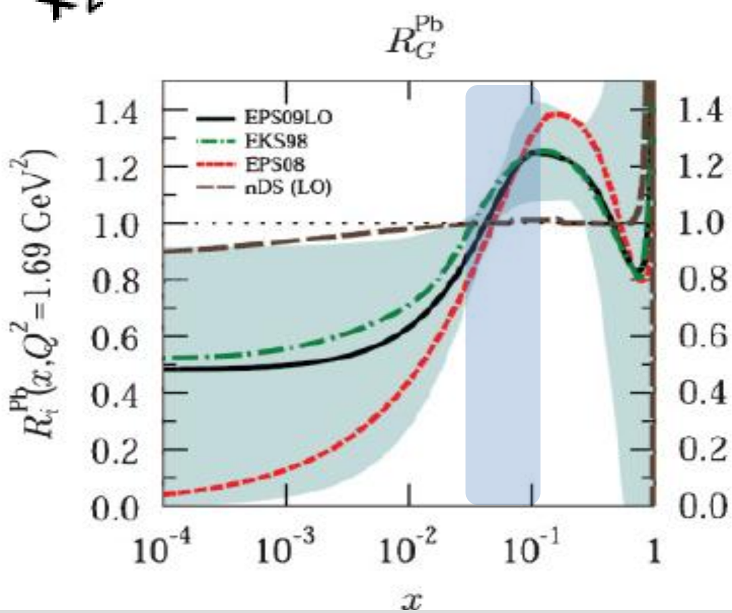
2 → 2



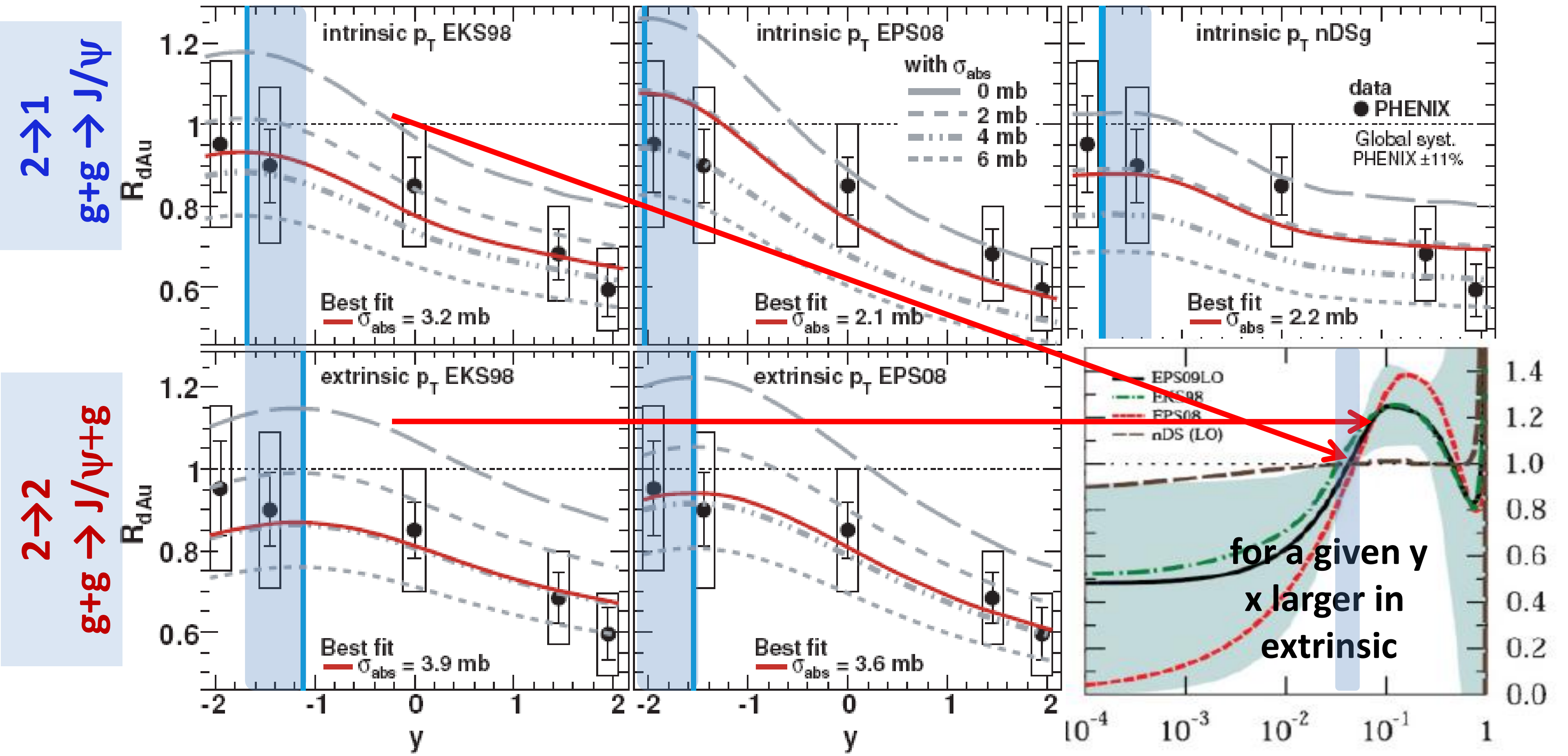
For a given set (y, p_T):
extrinsic scheme:
more freedom for x

for a given y => larger x in extrinsic scheme

We expect different shadowing effects in both cases



Results d+Au @ RHIC: J/ψ rapidity dependence of R_{dAu}



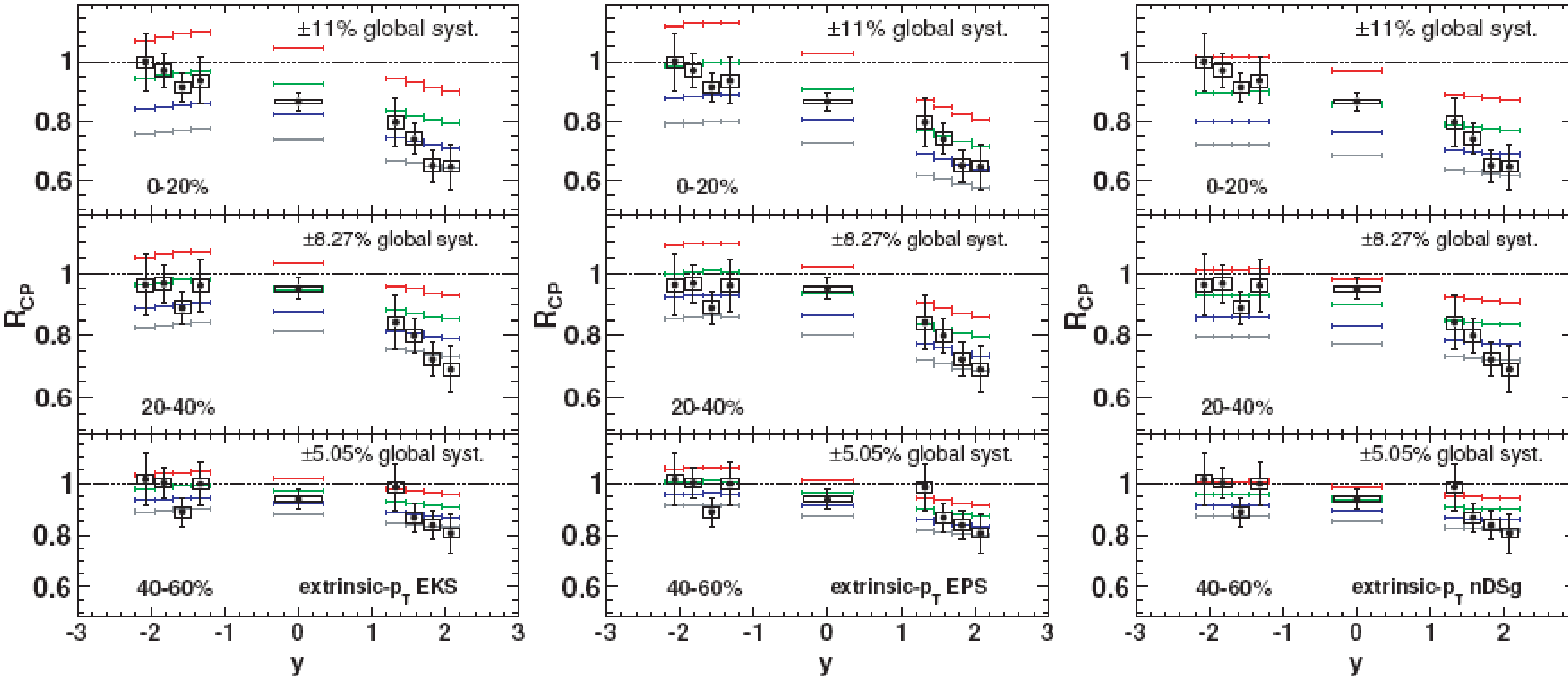
arXiv:0912.4498

- shadowing depends on the partonic process: 2→1 or 2→2
- antishadowing peak shifted toward larger y in the extrinsic case
- in order to reproduce data: **nuclear absorption**

σabs extrinsic > σabs intrinsic   the kinematics matter for the extraction of σabs

Results d+Au @ RHIC: J/ψ rapidity dependence of R_{CP}

Extrinsic scheme: **σ_{abs}= 0, 2, 4, 6 mb in 3 shadowing models**



Data dependence on y:

- Suppression for the most forward points in the three centrality ranges
- In the negative rapidity region, dominated by large x, no (or compensated) nuclear effects

Data at back and mid-y can be described with a σ_{abs} of 2–4 mb, while the most forward points seem to decrease more than our evaluation

$\sigma_{abs}(y)$?

Fit of σ_{abs} with EKS, EPS and nDS(g) from R_{dAu} and R_{CP}

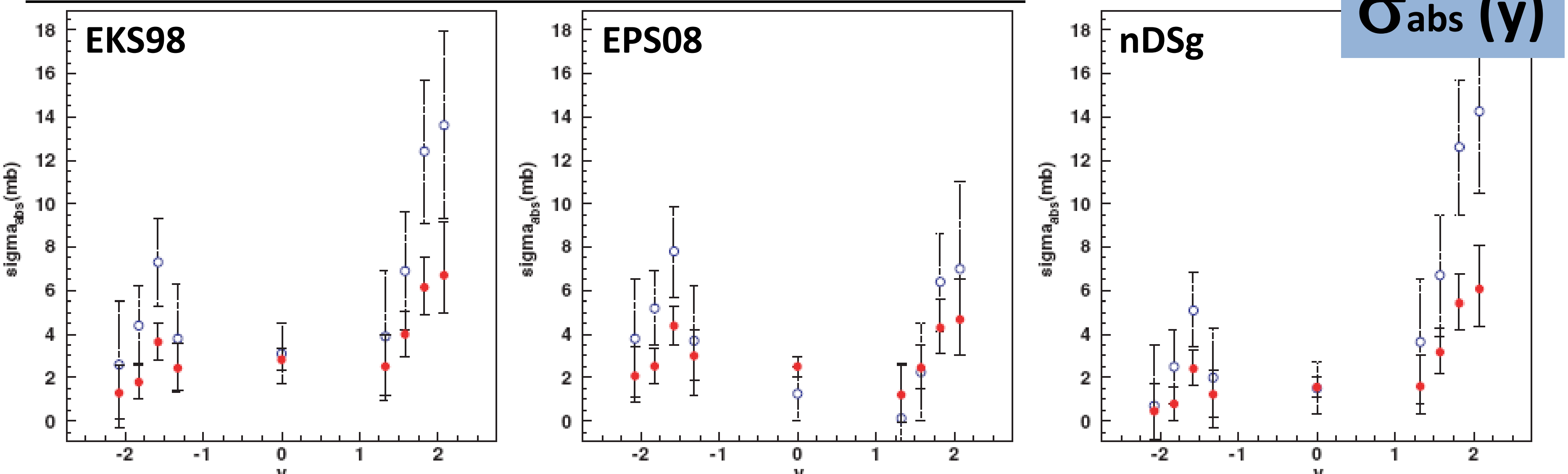
σ_{abs} and χ^2 from R_{dAu}	EKS		EPS		nDS(g) LO	
intrinsic	**3.20**	0.9	**2.11**	1.1	**2.21**	1.6
extrinsic	**3.90**	1.1	**3.60**	0.5	**3.00**	1.4

σ_{abs} int < σ_{abs} ext

σ_{abs} from R_{CP}	$y < 0$	$y = 0$	$y > 0$	All y
EKS98 Int.	5.2 ± 1.2	3.1 ± 1.3	9.5 ± 1.4	N/A
EKS98 Ext.	2.5 ± 0.5	3.2 ± 0.5	4.8 ± 0.7	3.2 ± 0.4
EPS08 Ext.	3.2 ± 0.5	2.5 ± 0.5	3.1 ± 0.6	2.9 ± 0.3
nDSg Ext.	1.4 ± 0.5	1.6 ± 0.5	4.0 ± 0.7	2.2 ± 0.3

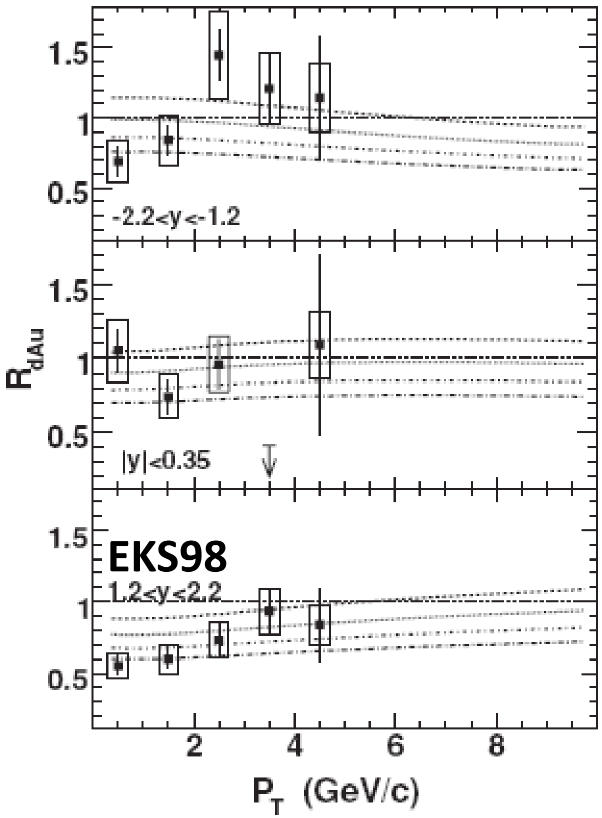
Intrinsic: increase of σ_{abs} with y
Extrinsic: softer increase of σ_{abs}
a constant behavior cannot be ruled out (see EPS08)

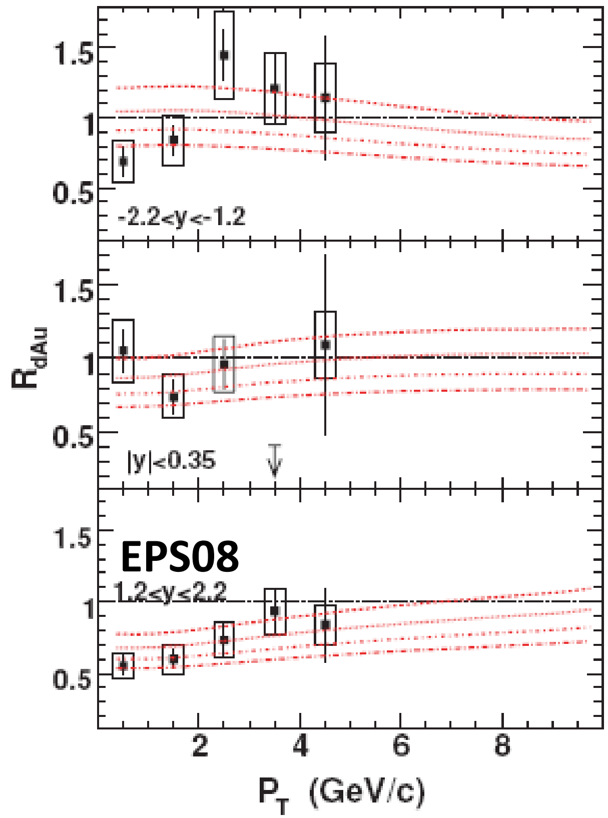
σ_{abs} (y)

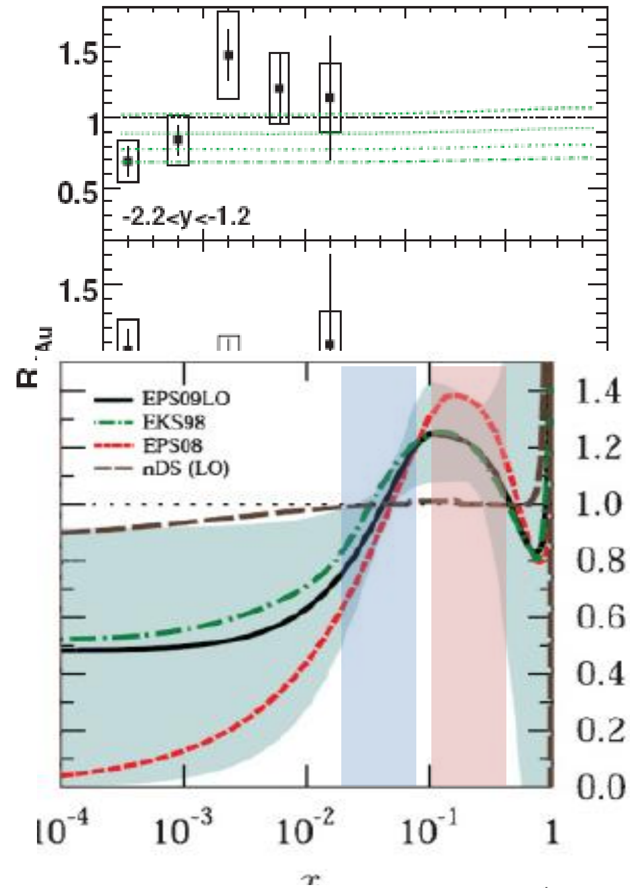


Results d+Au @ RHIC: J/ψ transverse momentum dependence

Extrinsic scheme: σ_{abs}= 0, 2, 4, 6 mb in 3 shadowing models







Growth of R_{dAu} not related to Cronin effect:

it comes from the increase of x for increasing P_T $\quad x_\perp \propto \left(m^2_{J/\psi} + p^2_\perp\right)^{1/2}$

- in the mid and forward-y region: x goes **through the antishadowing** region => enhancement in R_{dAu}
- In the backward region: x **sits in an antishadowing** region=> decrease in R_{dAu}

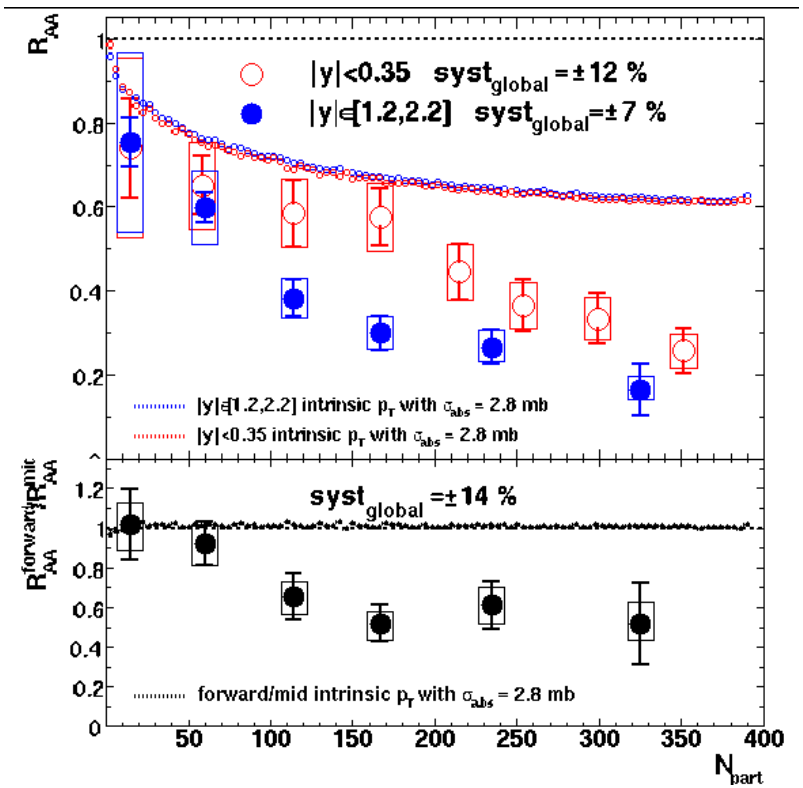
Results Au+Au @ RHIC: J/ψ centrality dependence of R_{AA}

Intrinsic scheme:

Same CNM suppression at forward and central rapidity

2→1

g+g → J/ψ

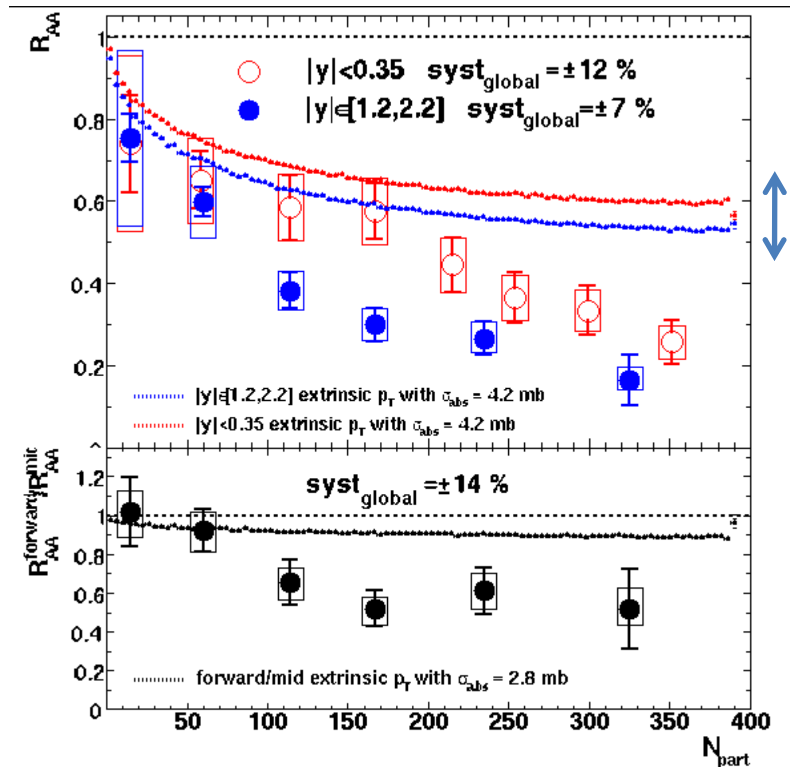


Extrinsic scheme:

More CNM suppression at forward than central rapidity

2→2

g+g → J/ψ+g



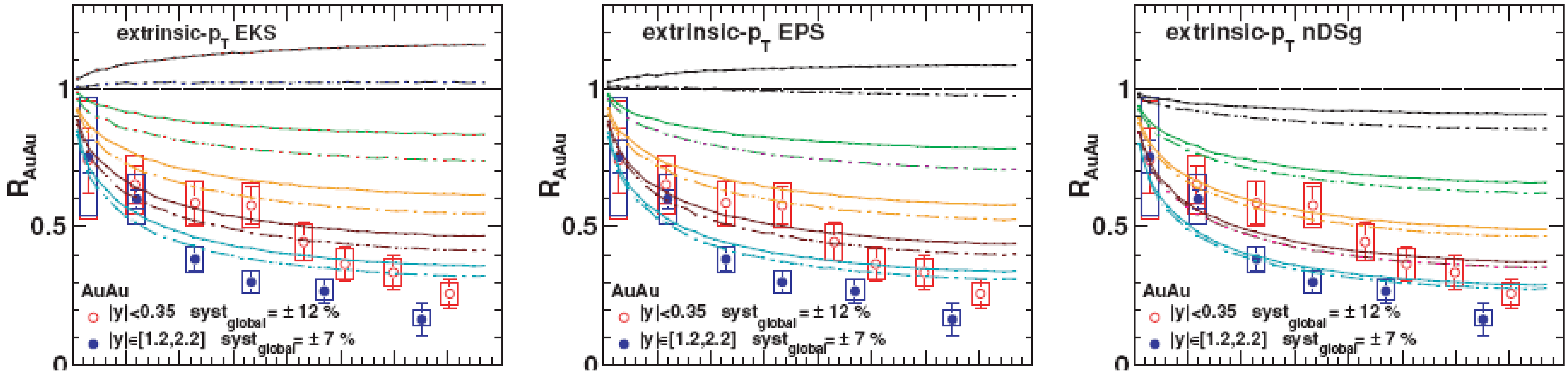
Extrinsic scheme : **RAA @ forward y < RAA @ mid y**

Hot Nuclear matter effects of course needed, but…

Less need for recombination effects

Results A+A @ RHIC: J/ψ centrality dependence of R_{AA}

Extrinsic scheme: σ_{abs}= 0, 2, 4, 6 mb in 3 shadowing models



R_{AA} systematically smaller in the forward region than in the mid-y region

The difference increases for more central collisions

This difference matches well the one of the data when σ_{abs} = 0

One needs a larger σ_{abs} if one wanted to reproduce the normalisation of the AuAu data, disregarding any effects of hot nuclear matter (HNM)

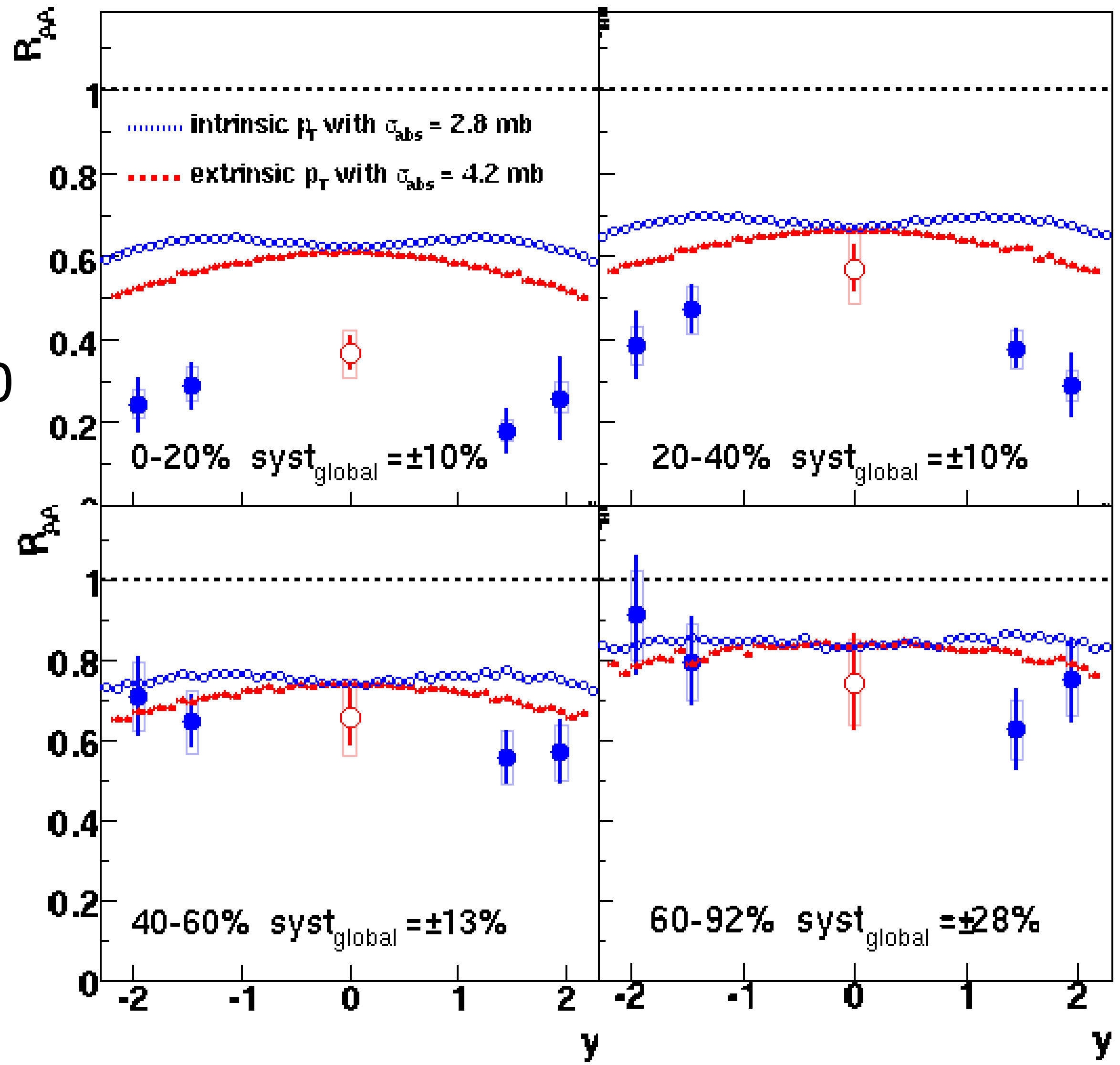
However, for such large σ_{abs}, surviving J/ψ from inner production points would be so rare that the difference between shadowing effects at mid and forward rapidities would nearly vanish

Note that for a σ_{abs} in the range of 2–4 mb, a difference remains

Results Au+Au @ RHIC: J/ψ rapidity dependence of R_{AA}

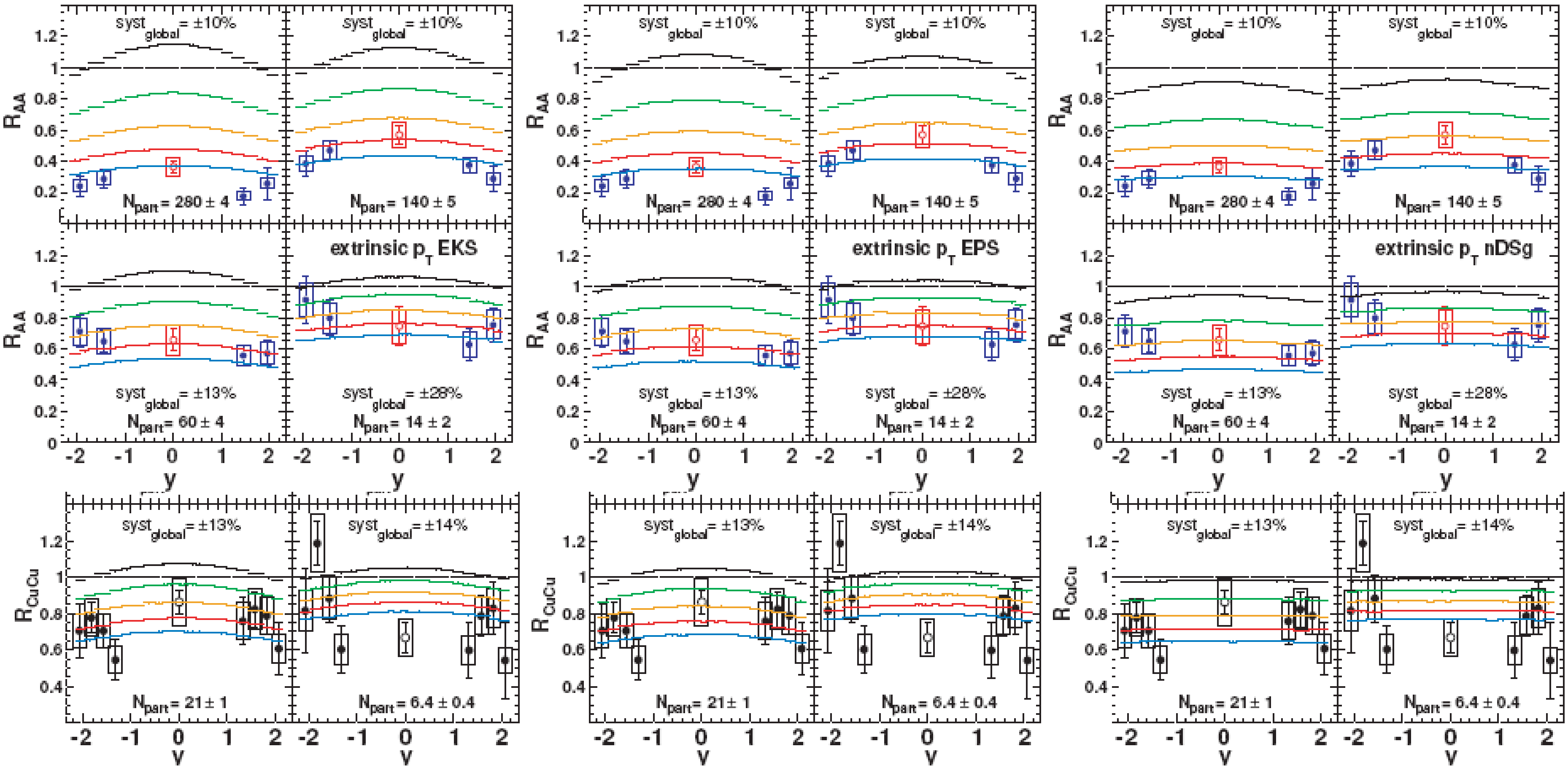
- Intrinsic: flat behaviour
- Extrinsic: maximun at y=0

Again, this indicates that **less recombination** would be required in the **extrinsic case**



Results A+A @ RHIC: J/ψ rapidity dependence of R_{AA}

Extrinsic scheme: **σ_{abs}= 0, 2, 4, 6 mb in 3 shadowing models**



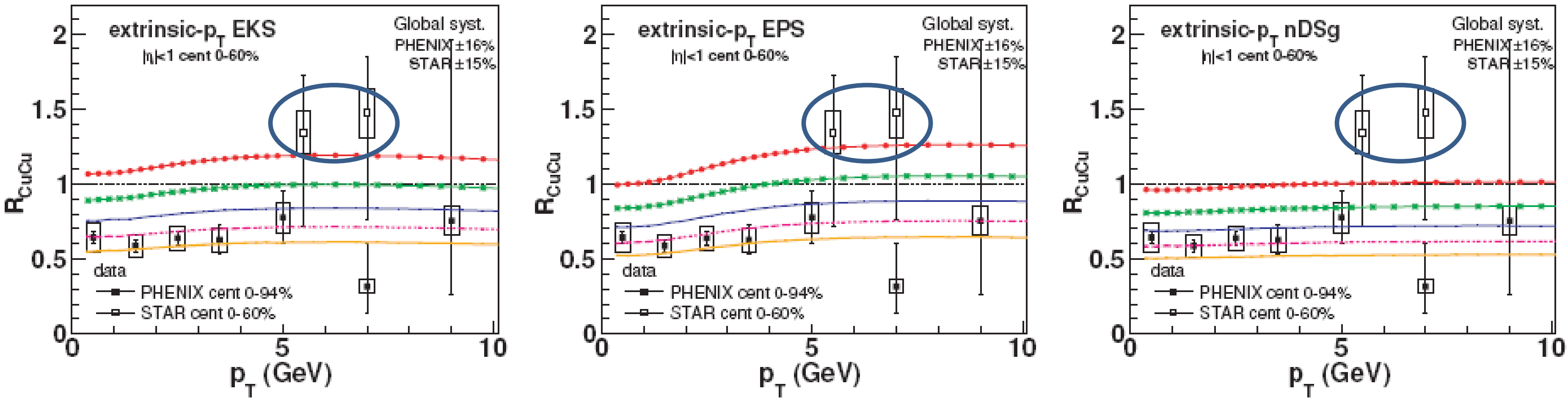
R_{AA} peaks at y = 0, reducing the need for recombination which concentrates at mid y

This effect is present in the three shadowing parametrizations we have used

This effect reduces with the increase of σ_{abs}

Results A+A @ RHIC: J/ψ transverse momentum dependence

Extrinsic scheme: σ_{abs}**= 0, 2, 4, 6 mb in 3 shadowing models**



R_{AA} increases with P_T partially matching the trend of PHENIX and STAR data

Nuclear modification factor larger than one for PT ≈ 8GeV (STAR results)?

J/ψ behavior closer to the one of photons than to the one of other hadrons?

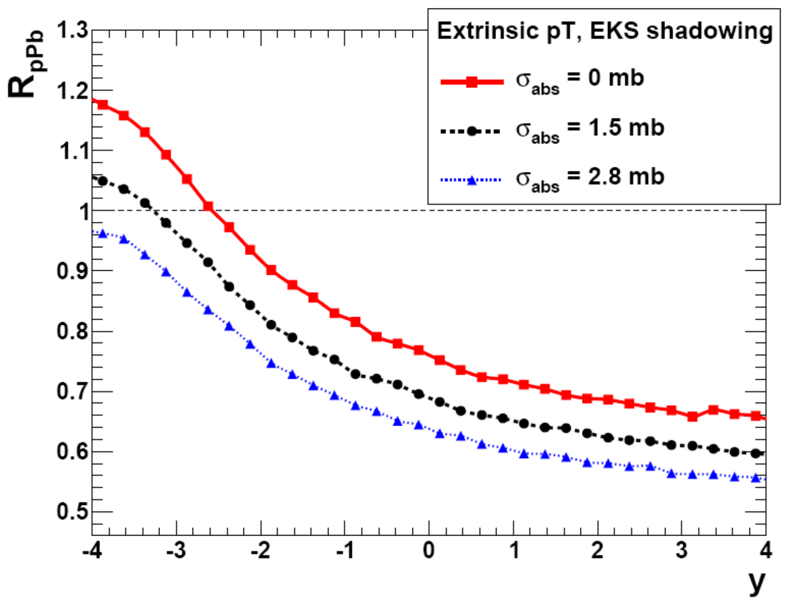
Hypothesis: **energy losss + Landau-Pomeranchuk-Migdal effect ?**

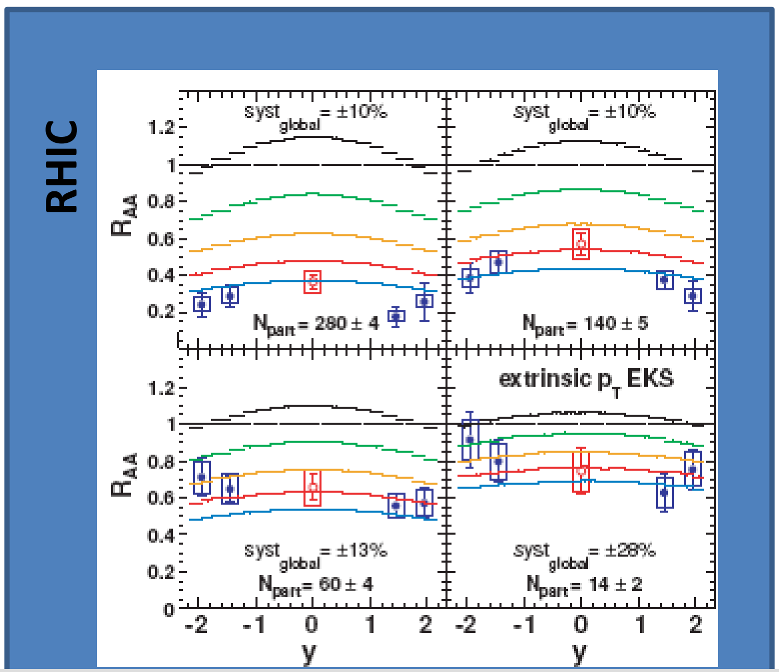
The **energy loss** of a colored object in CNM is limited to be constant

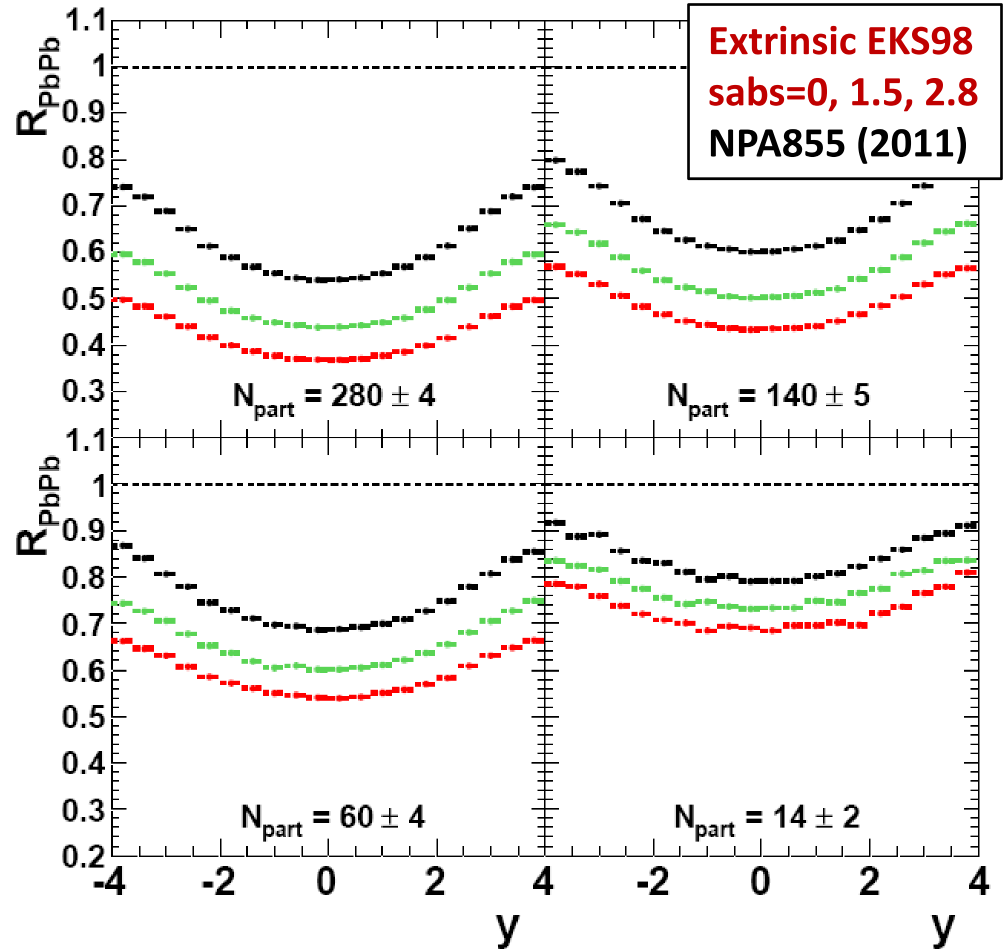
However, by the LPM effect , its magnitude will be larger for a CO than for a CS

Rather a colorless state than a colored one which propagates in the NM?

Work in progress: J/ψ @ LHC rapidity dependence



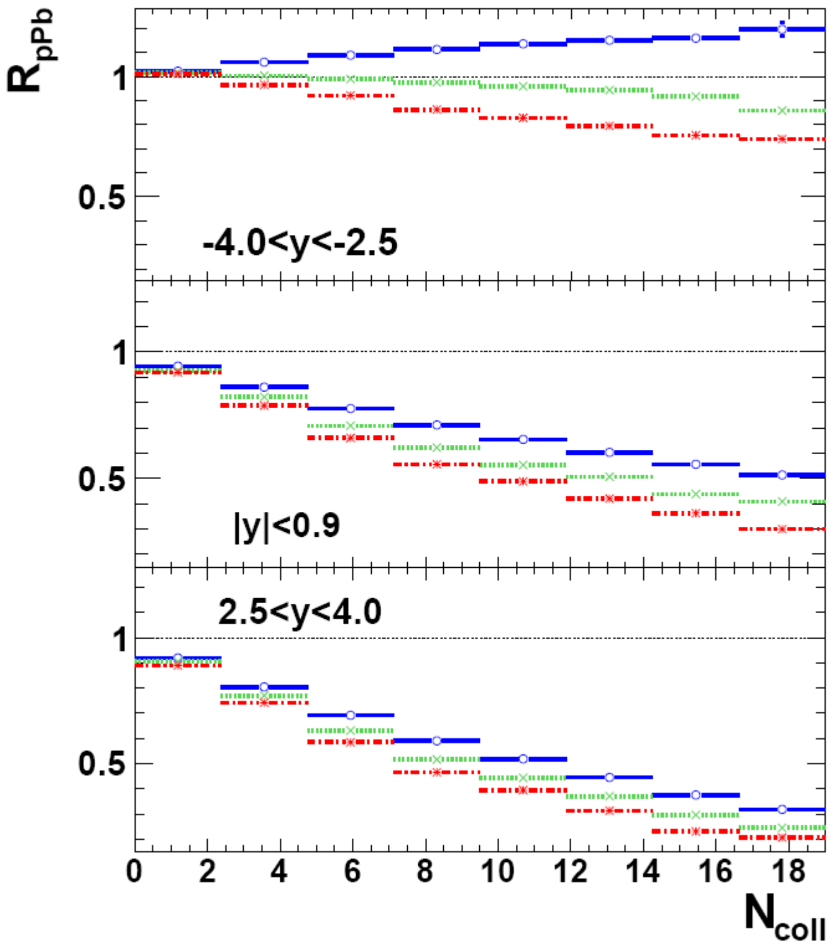


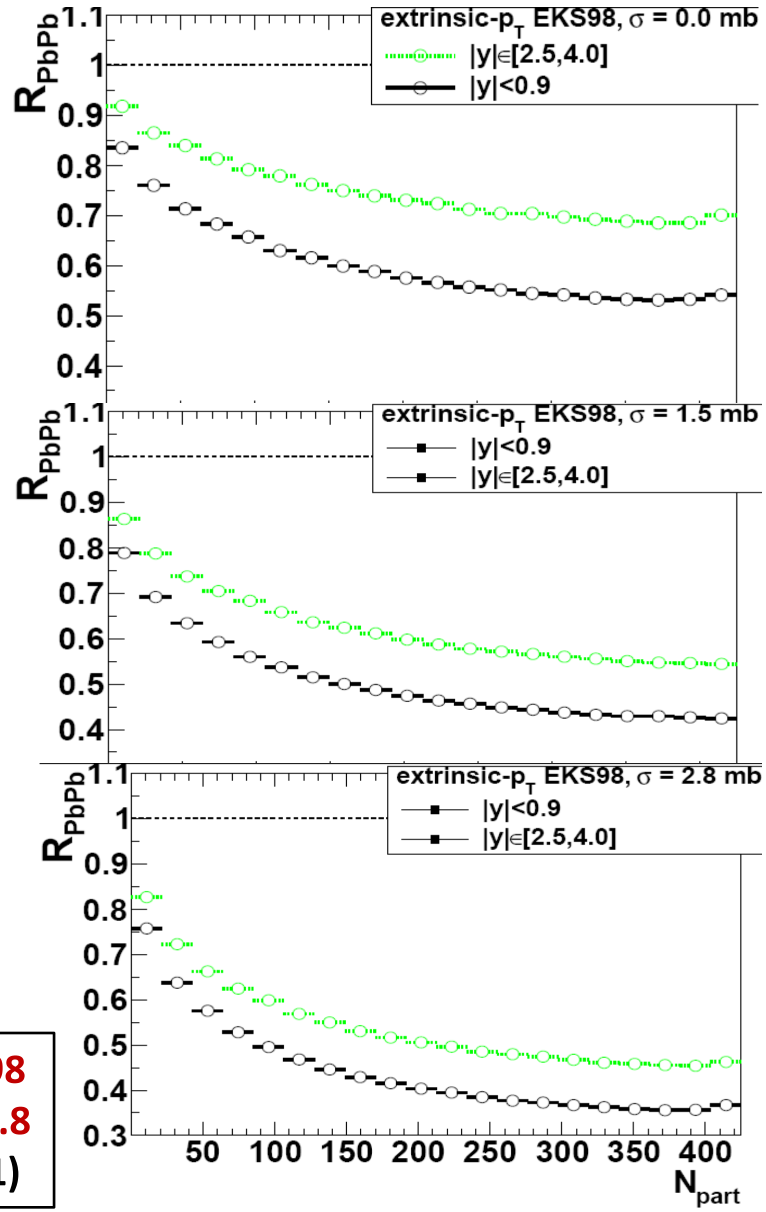


Opposite RAA behaviour vs rapidity:

- At RHIC=> stronger suppression at forward y
- At LHC => stronger suppression at mid y

Work in progress: J/ψ @ LHC centrality dependence

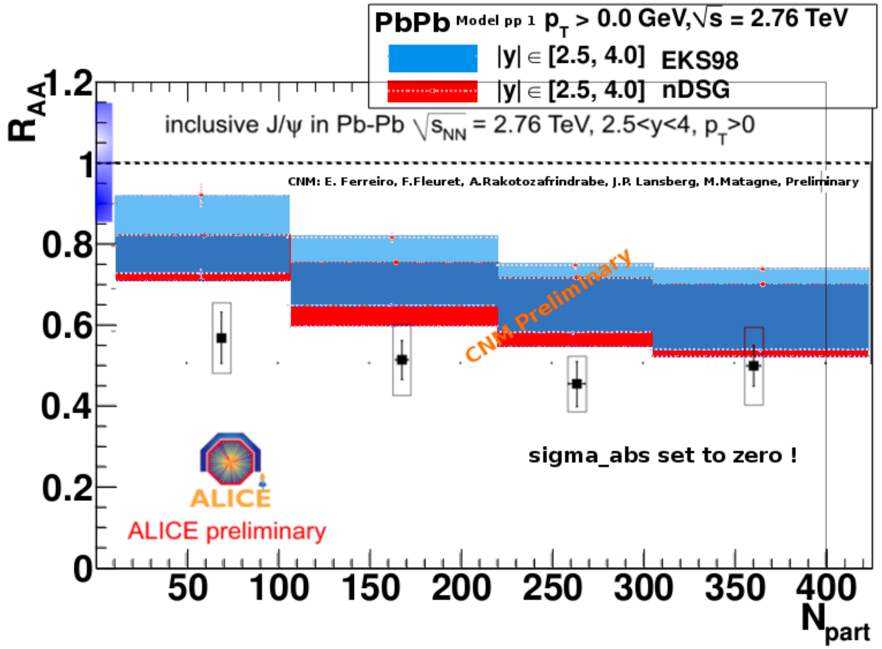




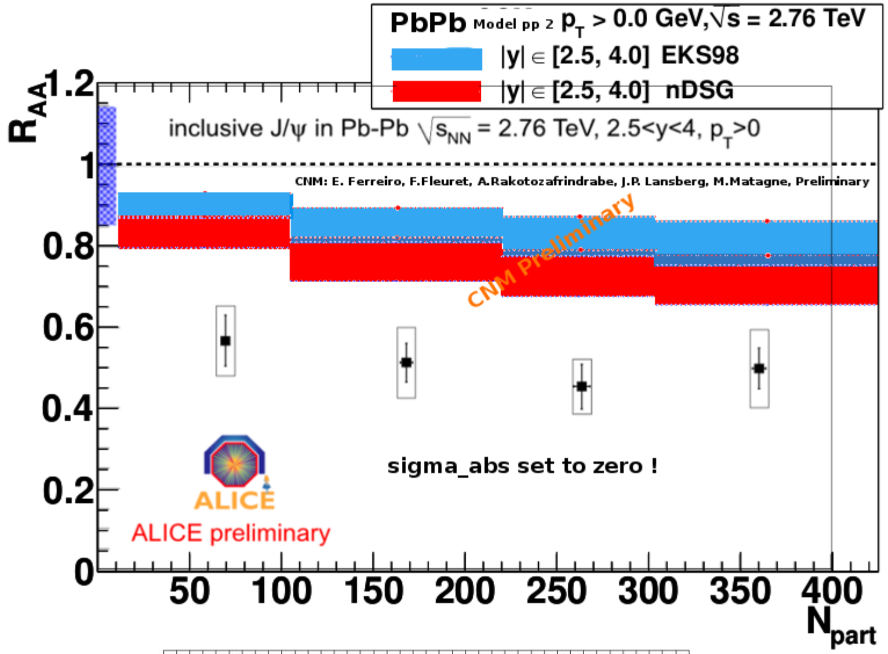
Extrinsic EKS98
sabs=0, 1.5, 2.8
NPA855 (2011)

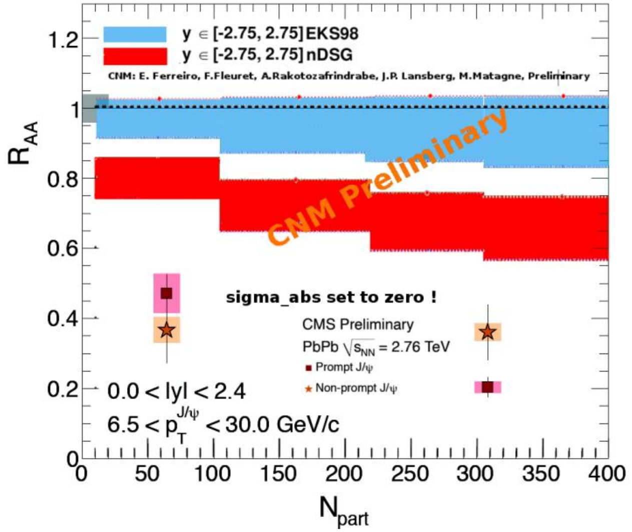
Work in progress: J/ψ @ LHC centrality dependence (2 → 2)

“CEM NLO” before k_T smearing



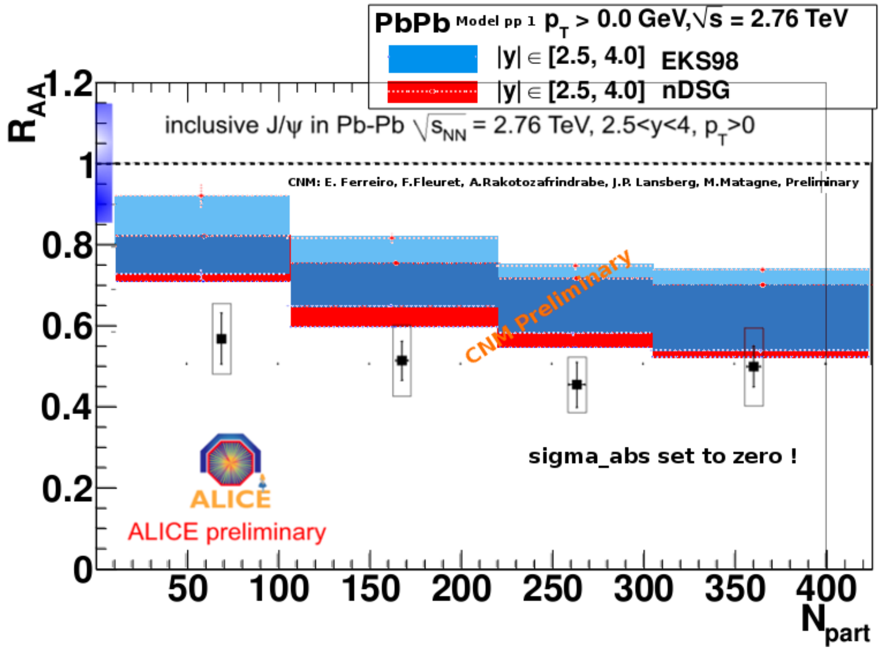
“Traditional” 2 → 2



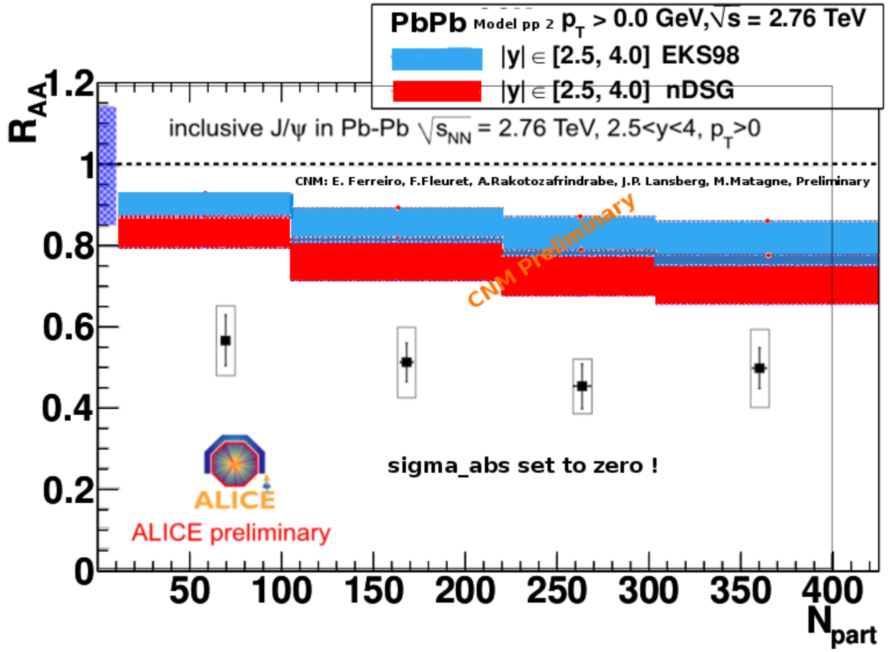


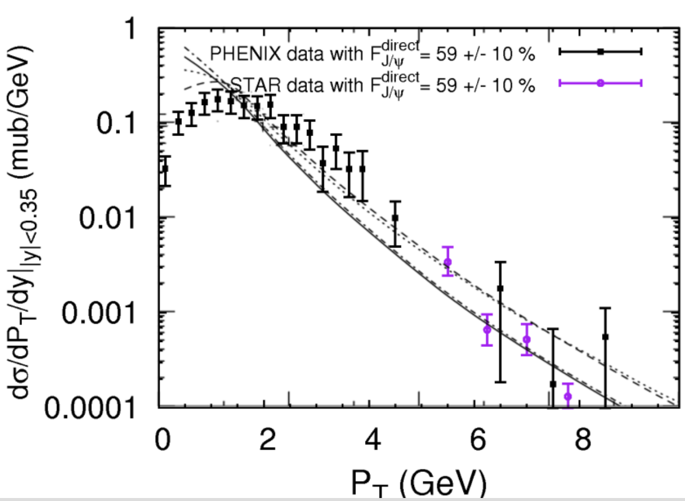
Work in progress: J/ψ @ LHC centrality dependence (2 → 2)

"CEM NLO" before k_T smearing

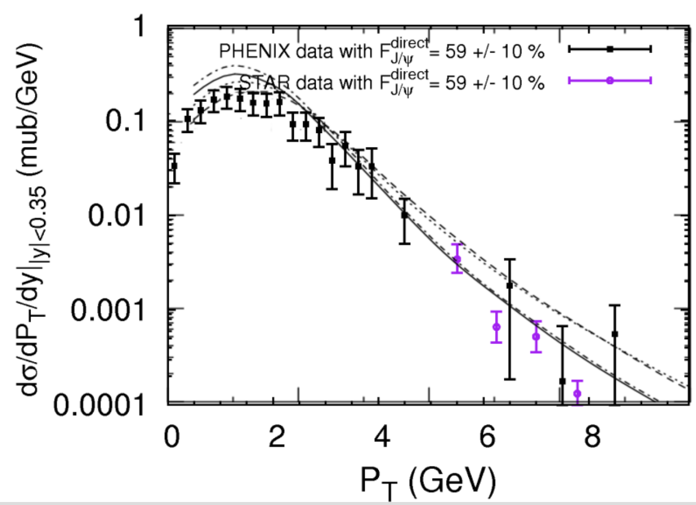


"Traditional" 2 → 2



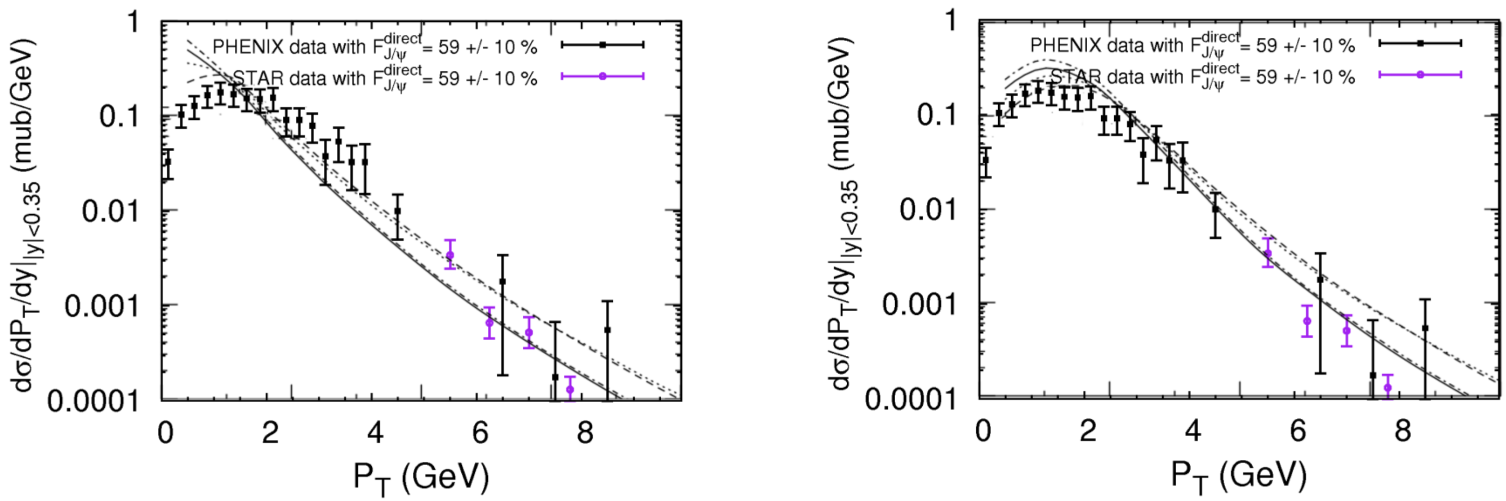


underlying partonic model



Note on the underlying partonic model

- **2 different 2-> 2 models** can give **different** results
- Example : with the existing code for CEM @ NLO, the kt smearing procedure is applied after the (x_1,x_2) integration

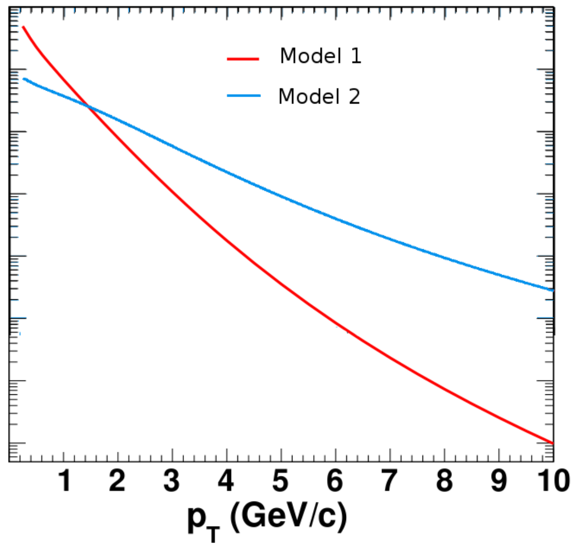


- Before the smearing (left) the distribution overhsoots the data
- More weight on low pT's=> the distribution used is closer to a 2 -> 1 process
- The CEM @ NLO is a **mix** between

a pure collinear 2->2 and a pure 2->1 with intrinsic kt

Note on the shadowing and its uncertainties at LHC energies

- As we have seen, **different 2->2 partonic** models can give **different results**
- We have used 2 'toy' models :

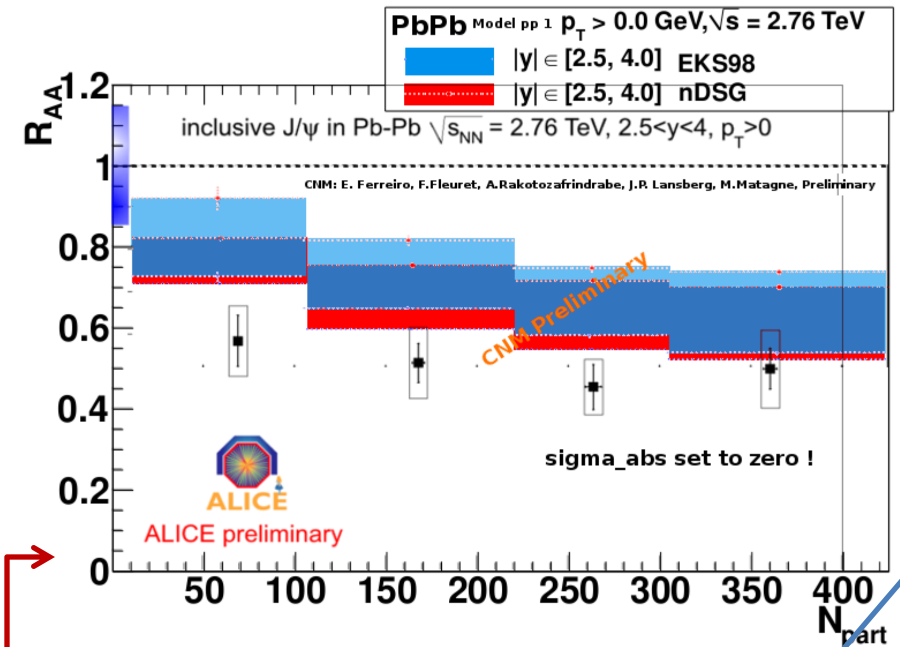


- We use nDSg and EKS98 as possible gluon shadowings (non-exhaustive)

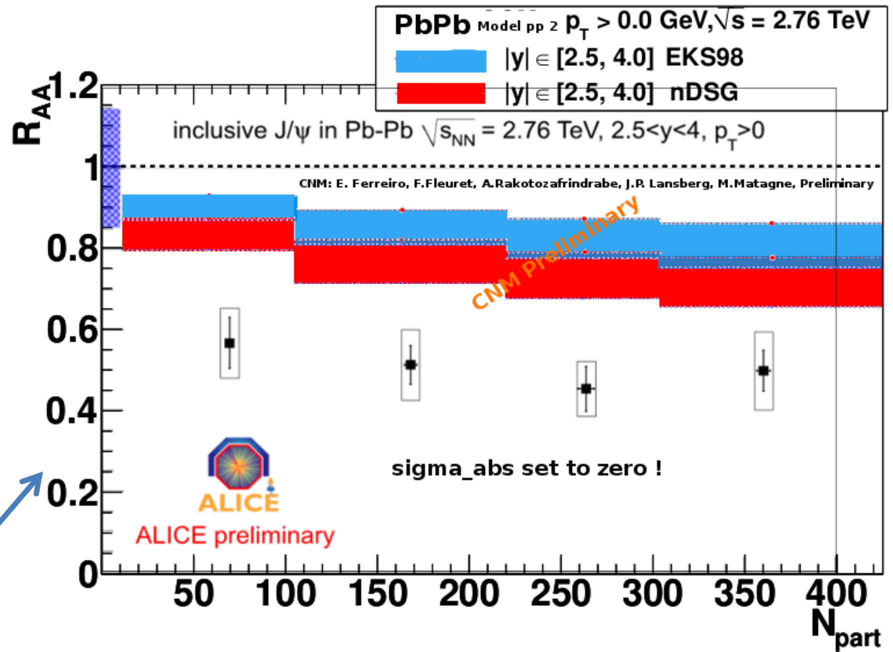
- Finally we vary μ_F from 0.5 x m_T to 2 x m_T (as done in *pp* for $g(x,\mu_F)$)

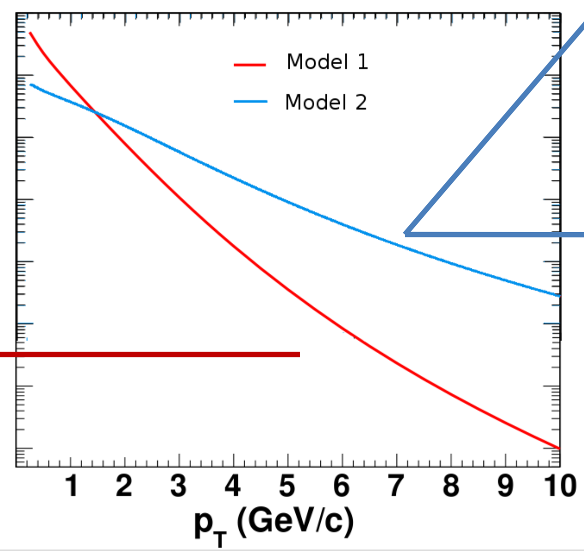
Work in progress: J/ψ @ LHC centrality dependence (2 → 2)

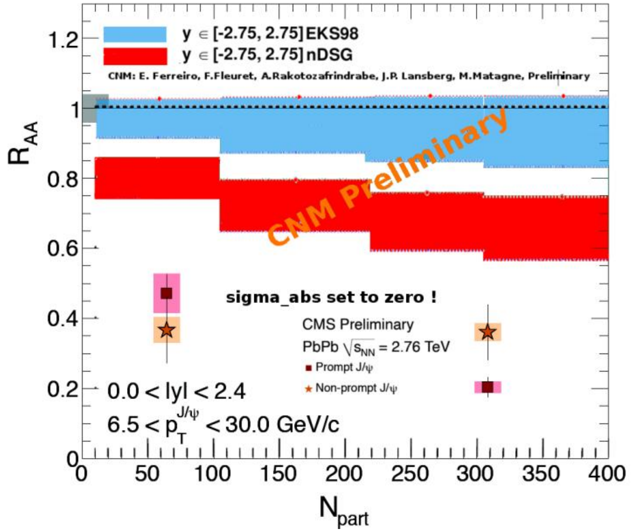
"CEM NLO" before k_T smearing



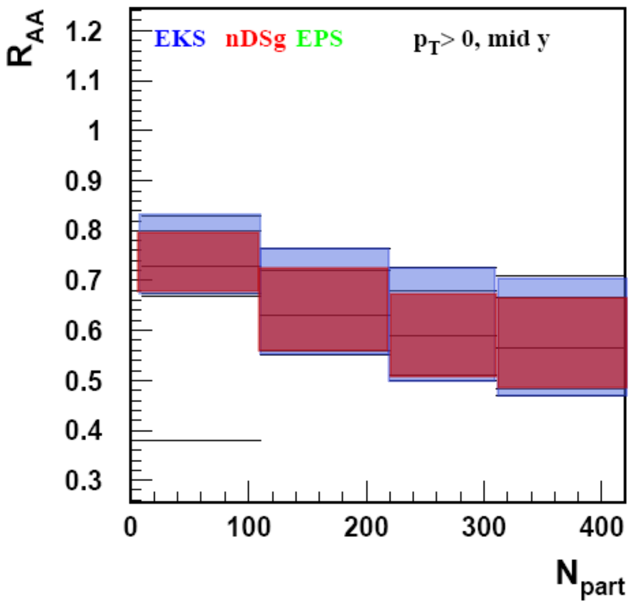
"Traditional" 2 → 2

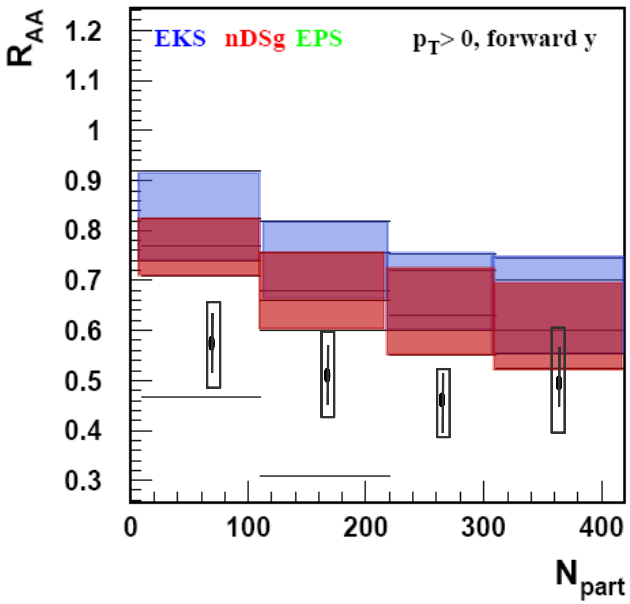




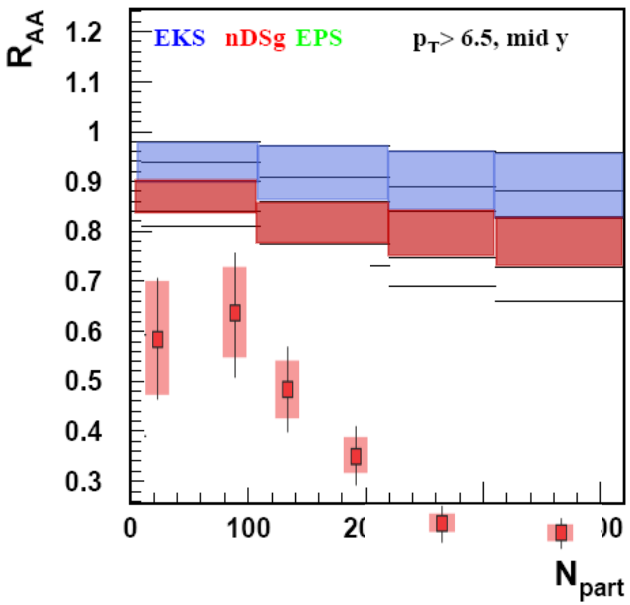


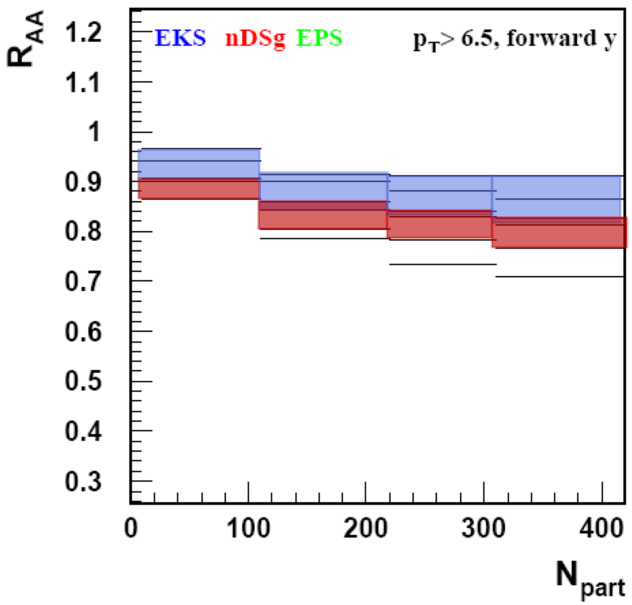
CEM NLO inspired 2-> 2 peacked at low pT (to be smeared out)





For pT>0:
Stronger shadow suppression at mid rapidity

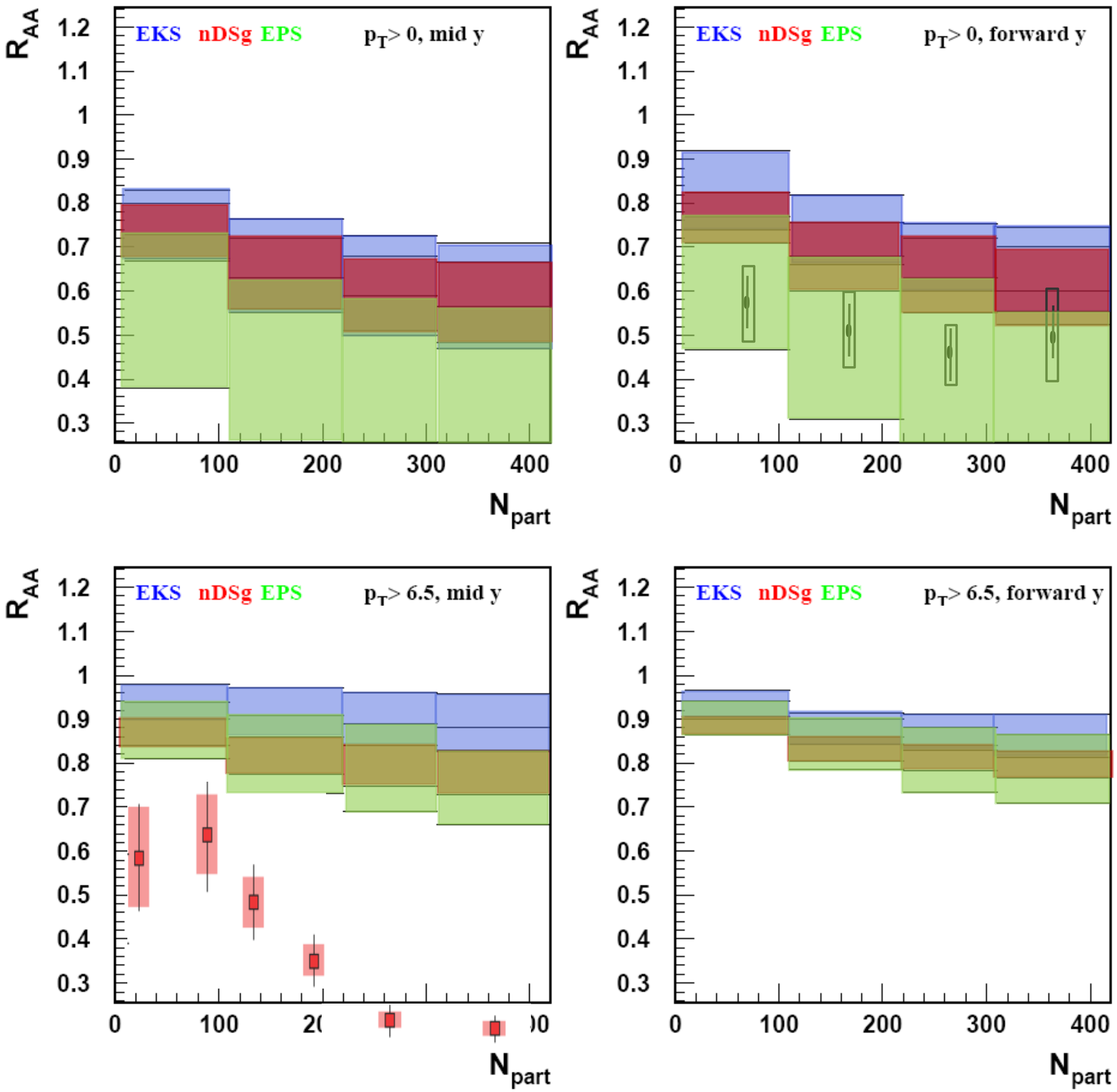




For pT>6.5:
Slightly stronger shadowing suppression at mid rapidity

nDSg shadowing >
EKS shadowing

CEM NLO inspired 2-> 2 peacked at low pT (to be smeared out)



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Stronger shadow suppression at mid rapidity

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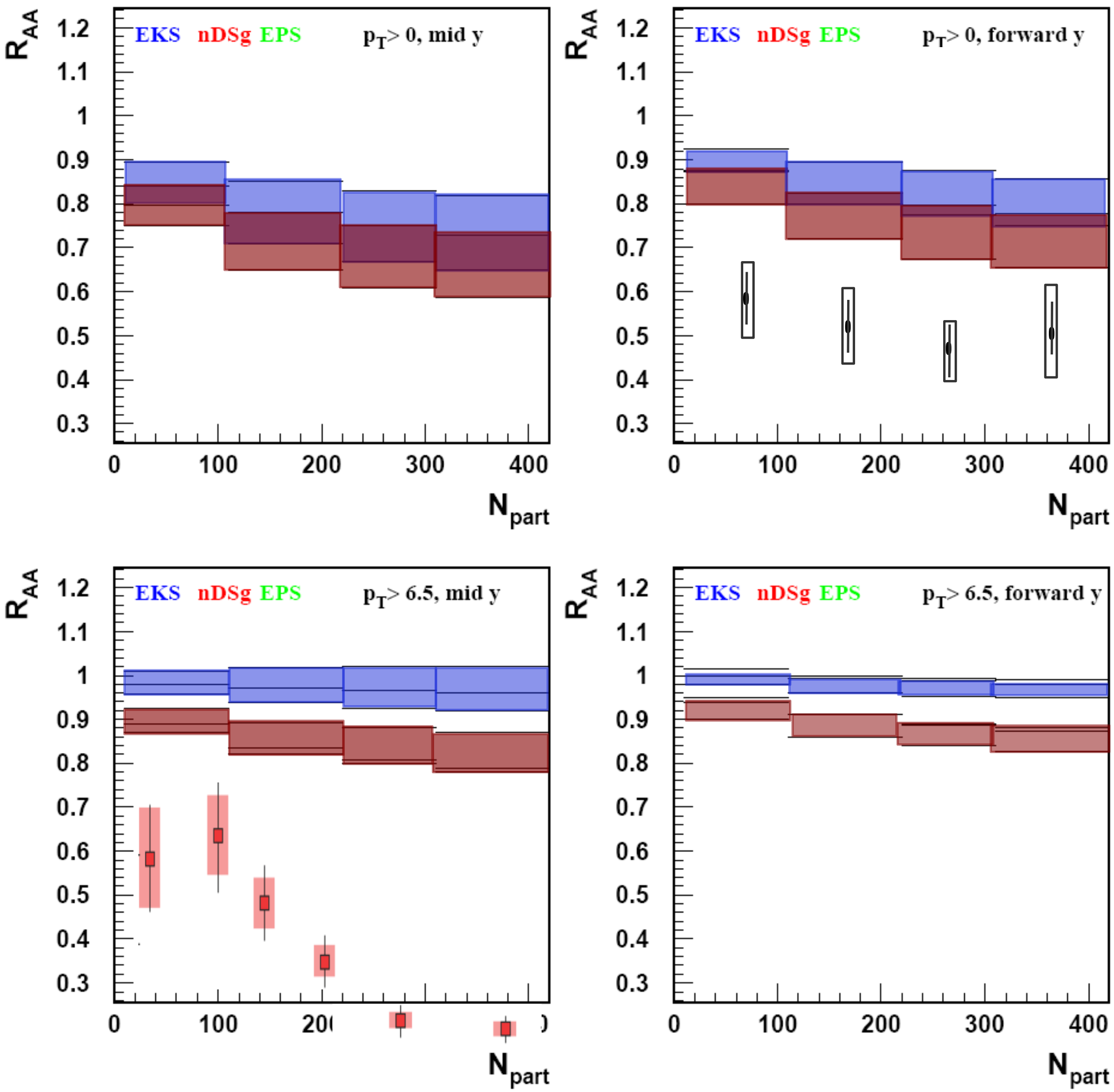
“Traditional” 2 -> 2



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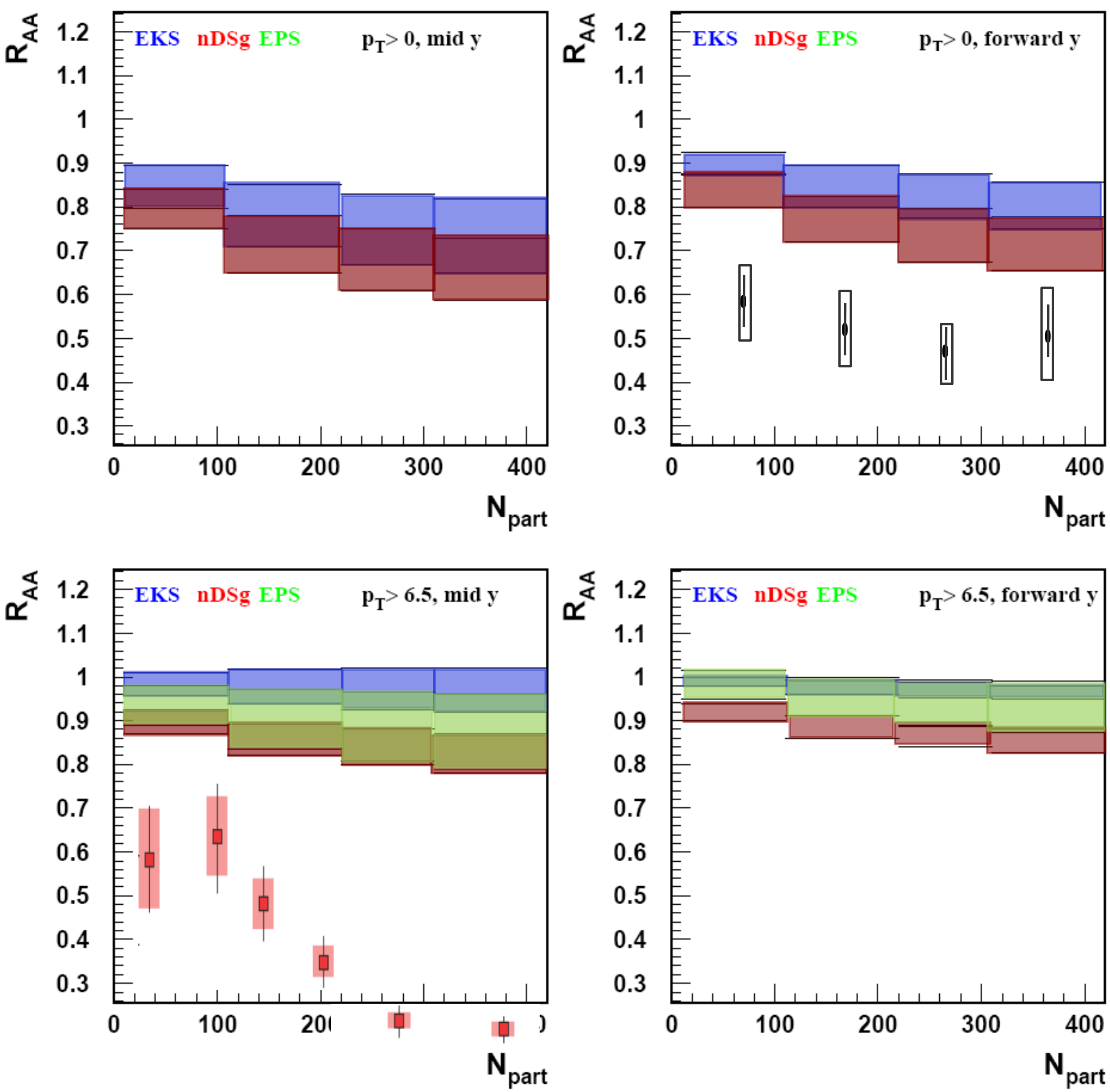

For pT>0:
Stronger shadow suppression at mid rapidity

For pT>6.5:
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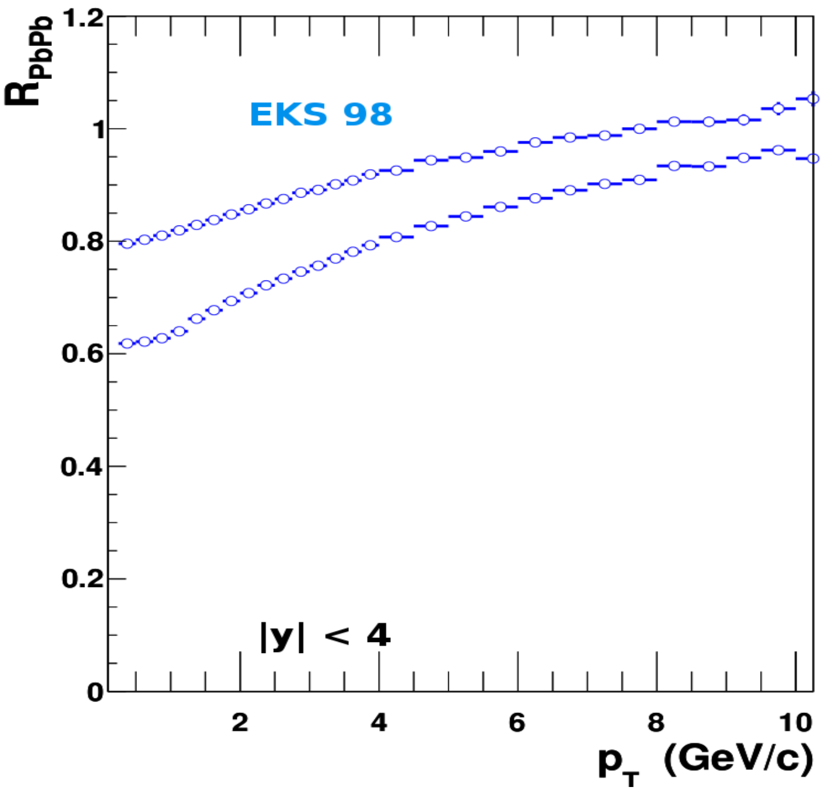
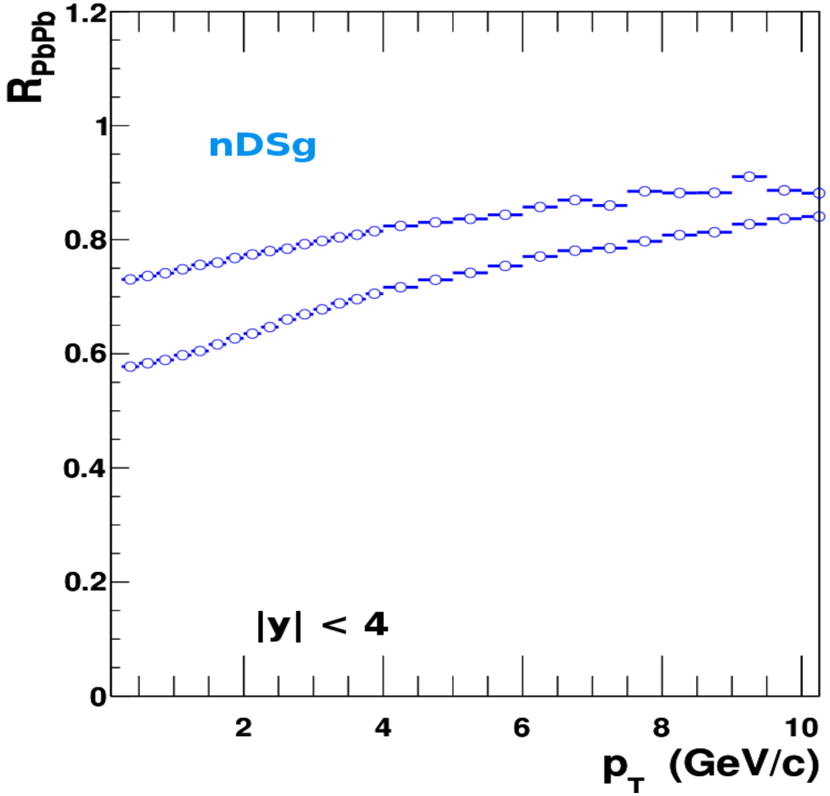
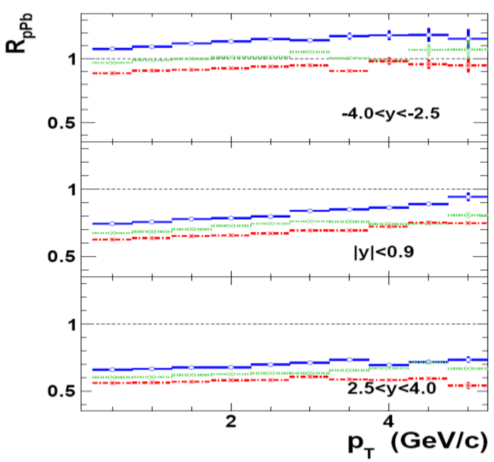
nDSg shadowing >
EKS shadowing

Work in progress: J/ψ @ LHC pT dependence







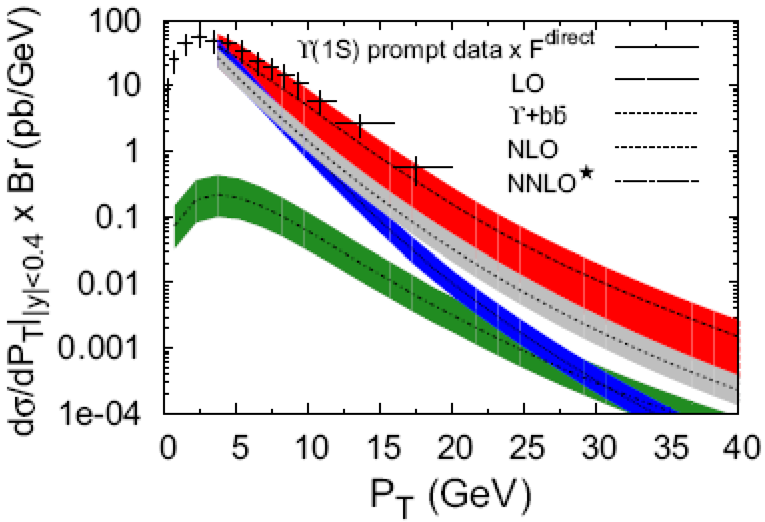
Shadowing decreases with increasing pT

Stronger variation for EKS than nDSg

EKS: 25-40%

nDSg: 15-30%

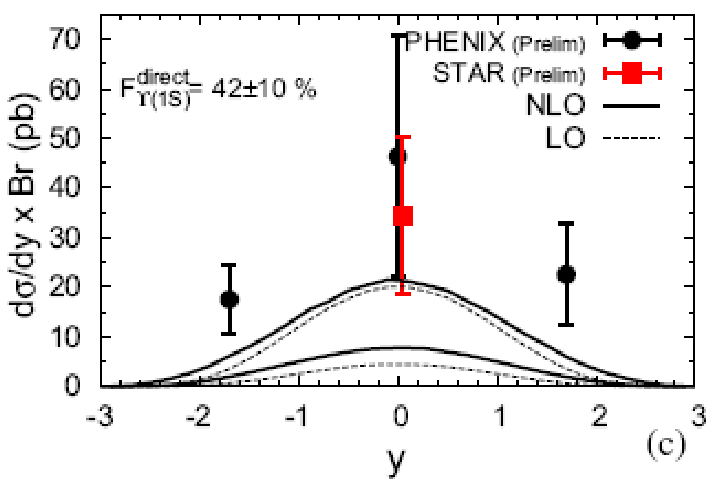
On the kinematics of Υ production



Results at 1.8 TeV:

- CSM describes well $d\sigma/dpT$ at NNLO
- LO CSM is sufficient to describe low pT data

2 → 2 process



Results at 200 GeV:

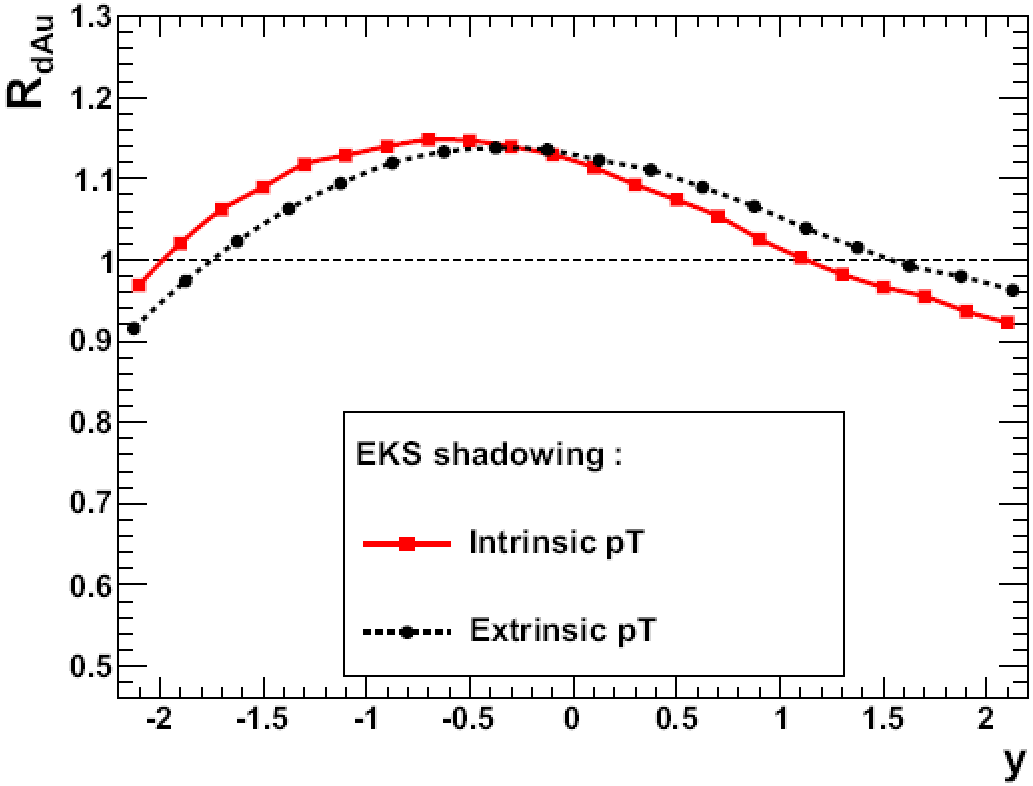
LO upper line: *mb = 4.5 GeV, μR = MT , μF = 2MT*

LO lower line: *mb = 5.0 GeV, μR = 2MT , μF = MT*

We take the parameters of the upper curve in the following.

Results for d+Au: Υ rapidity dependence

Intrinsic vs extrinsic scheme

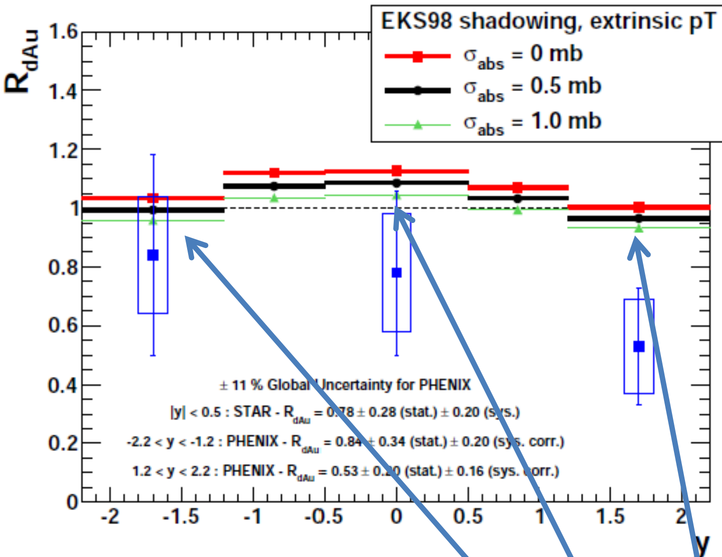


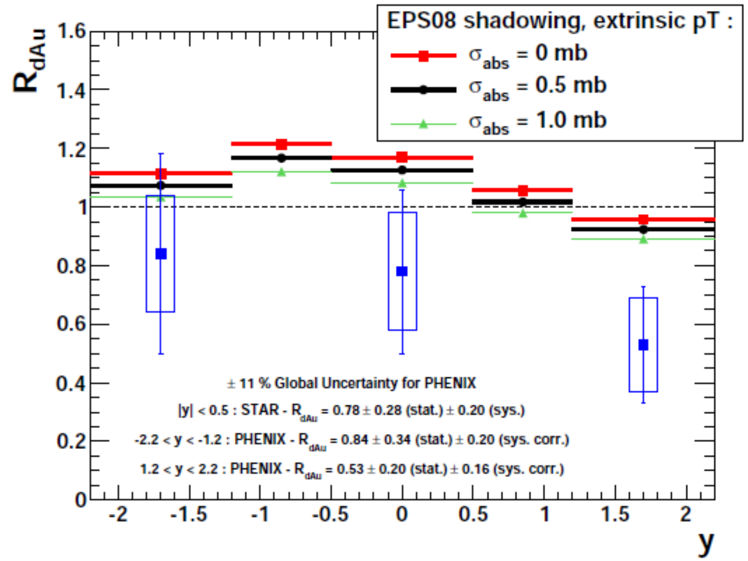
- Different shadowing effects in the 2 approaches

- Antishadowing peak shifted toward larger y in the **extrinsic** case

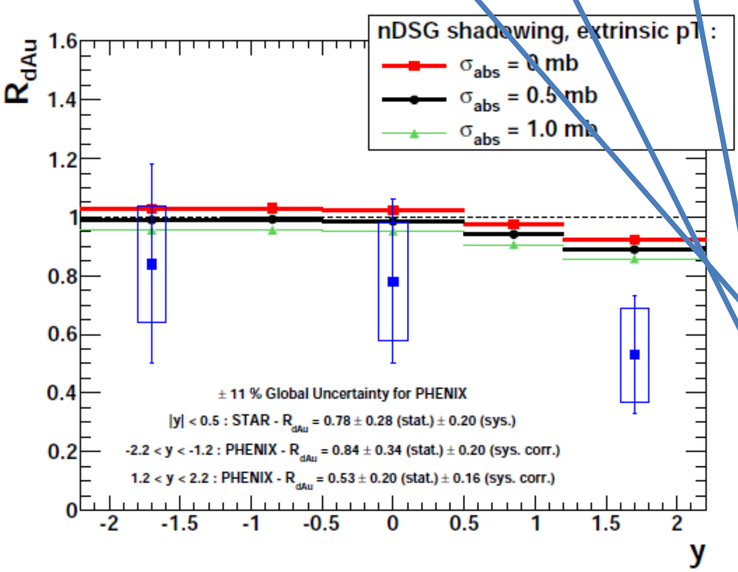
Results for d+Au: Υ rapidity dependence

Extrinsic scheme: σ_{abs}=0 mb, σ_{abs}= 0.5mb , σ_{abs}= 1 mb in 3 shadowing models





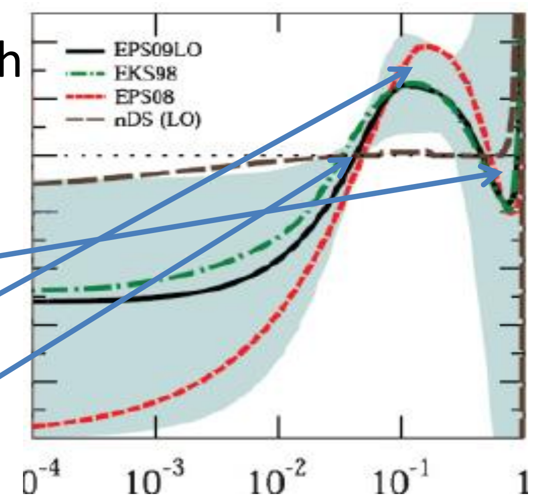
- backward: ok within uncertainties
- central: reasonable job
- forward : clearly too high



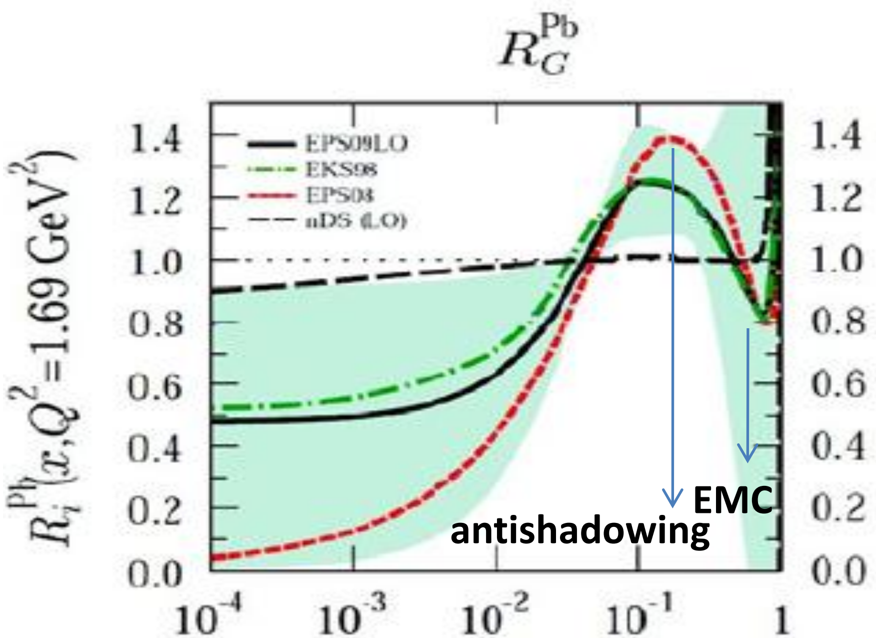
Physical interpretation

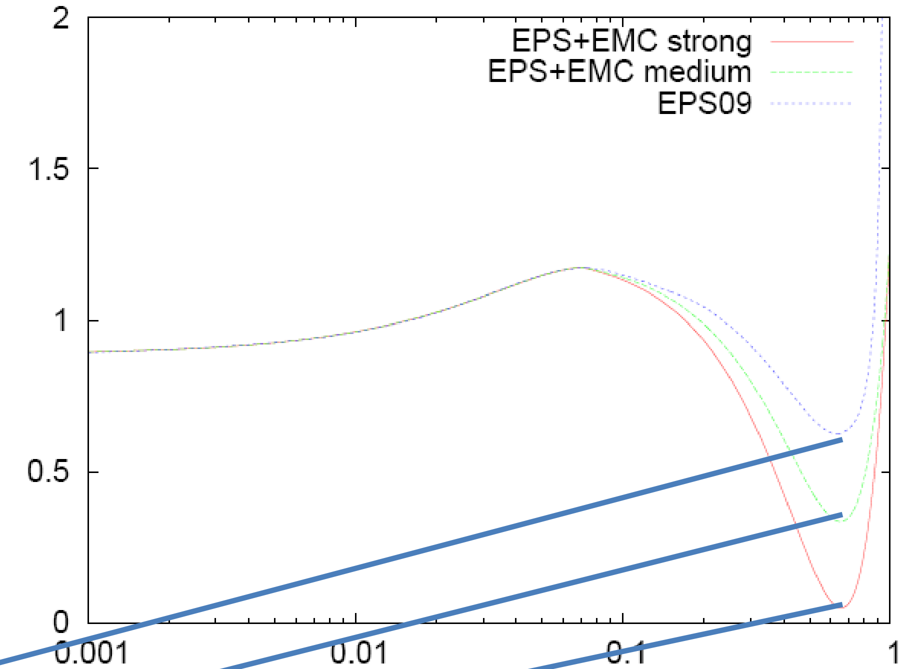
- backward: EMC effect
- central: antishadowing
- forward : shadowing≈1

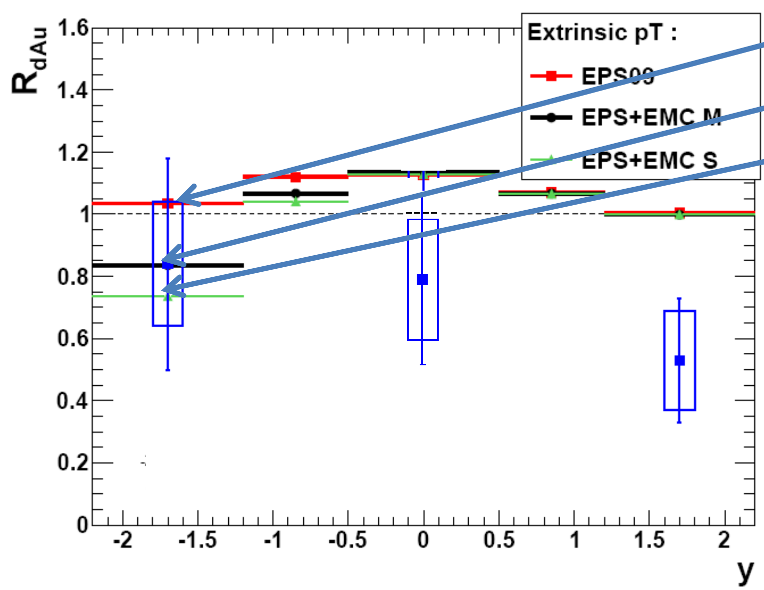
energy loss is needed



Work in progress: EMC effect







Let us try to increase the suppression of *g(x)* in the EMC region, keeping momentum conservation : $\int xg(x)\,dx = \mathrm{Cte}$

Works better for backward region

Work in progress: Energy loss effect

- **Basic idea:** An energetic parton traveling in a large nuclear medium undergoes multiple elastic scatterings, which induce gluon radiation
  => *radiative energy loss* (BDMPS)

- **Intuitively:** due to parton energy loss, a hard QCD process probes the incoming PDFs at higher x, where they are suppressed, leading to nuclear suppression

- **The problem:** This energy loss is subject to the LPM bound
  => Δ E is limited and does not scale with E (Brodsky-Hoyer)

- **At RHIC and LHC** (contrary to SPS), typical partons (for x1 ~ 10^{-2}) have energies of the order of hundreds of GeV in the nucleus rest frame
  => radiative energy loss has a negligible effect on the parton x_1

Work in progress: Energy loss effect

• Still, in order to explain large x_F data at RHIC, it would be useful to have

***=> a fractional energy loss*: Δ E α E**

(Old idea by Gavin Milana, thought to be ruled out by LPM bound)

• Recently (Arleo, Peigner, Sami arxiv:10006.0818) it has been probed that the **notion of radiated energy associated to a hard process is more general than the notion of parton energy loss**.

The medium-induced gluon radiation associated to large-x_F quarkonium hadroproduction:

- **arises from large gluon formation times t_f >> L**
- **scales as the incoming parton energy E**
- **cannot be identified with the usual energy loss**
- **qualitatively similar to Bethe-Heitler energy loss**
- **the Brodsky-Hoyer bound does not apply for large formation times**

Thus, the Gavin-Milana assumption of an “energy loss” scaling as E turns out to be qualitatively valid for quarkonium production provided this “energy loss” is correctly interpreted as the radiated energy associated to the hard process, and not as the energy loss of independent incoming and outgoing color charges.

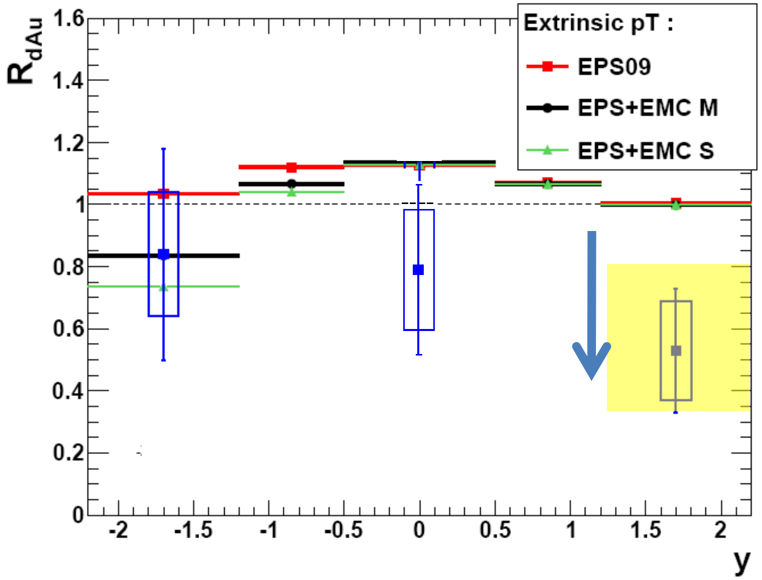
• Note that space effect through Sudakov suppression can also induce a fractionnal energy loss but for x_1 > 0.5 (Kopeliovich))

Work in progress: Energy loss effect

When the longitudinal momentum pL >> mT

$$\Delta E|_{\text{ind, large } x_F} \sim N_c \alpha_s \, \hat{\omega} \sim N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{M_\perp} \cdot E$$

$$\Delta x_1 = \frac{\Delta E}{E} \sim N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{M_\perp}$$

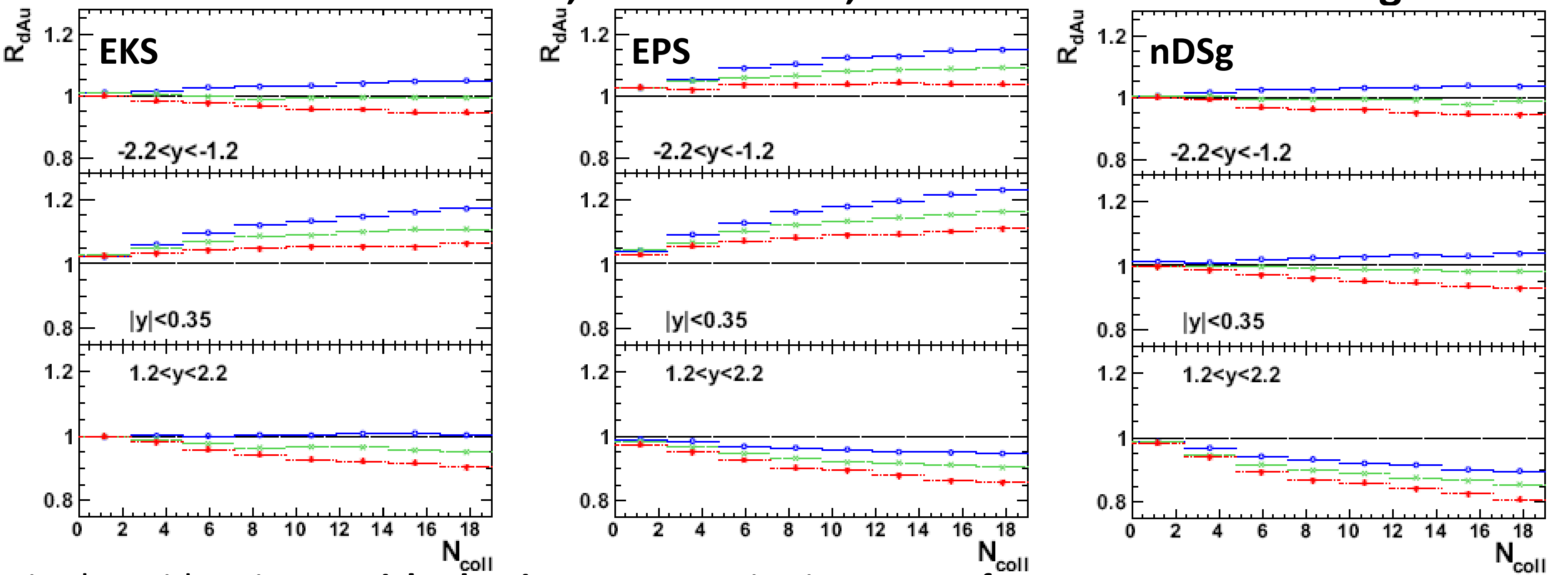


Due to the form of the gluon PDFs, the energy loss would be negligible in the central and backward rapidity regions.

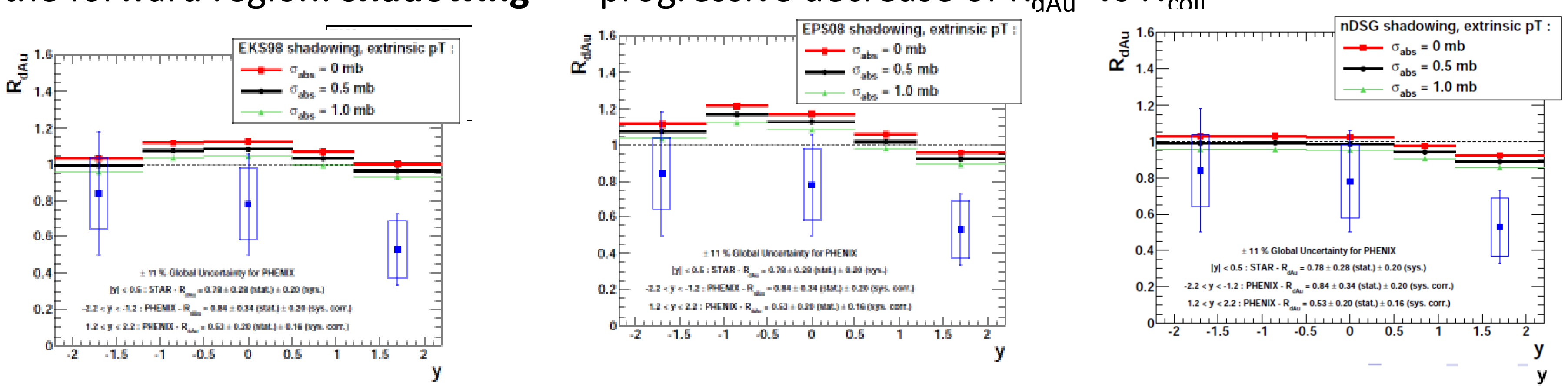
Note that, independently of the gluon PDF parameterization, this energy loss will induce a minimum suppression of 75% - 80% up to a maximum one of 40% in the forward region

Work in progress: Υ centrality dependence

Extrinsic scheme: σ_{abs}=0 mb, σ_{abs}= 0.5mb , σ_{abs}= 1 mb in 3 shadowing models

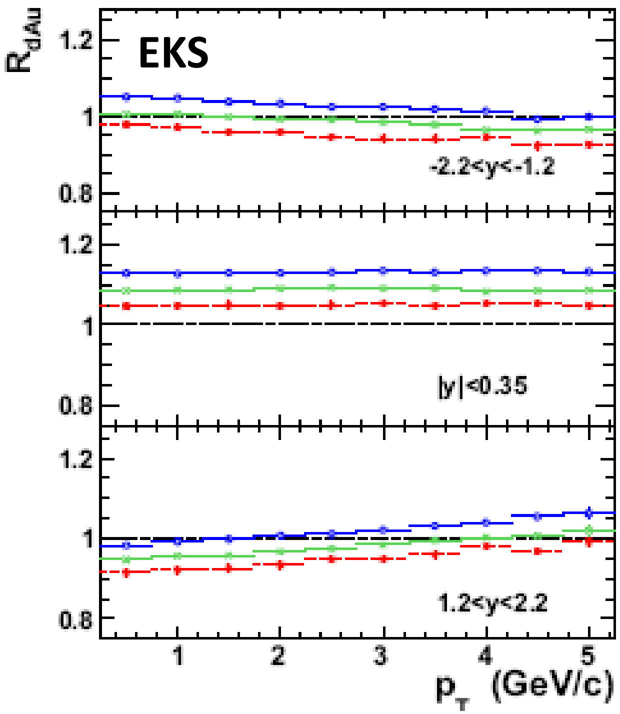


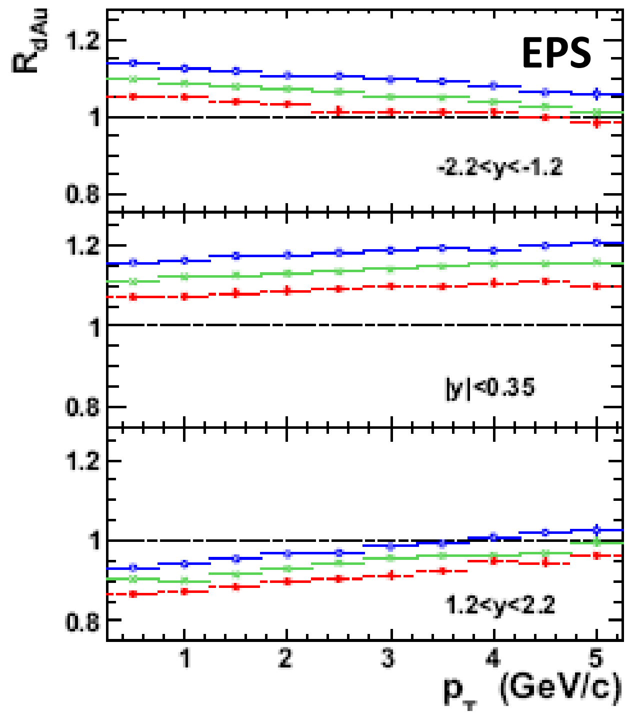
- in the mid region: **antishadowing**=>progressive increase of R_{dAu} vs N_{coll}
- in the forward region: **shadowing** => progressive decrease of R_{dAu} vs N_{coll}

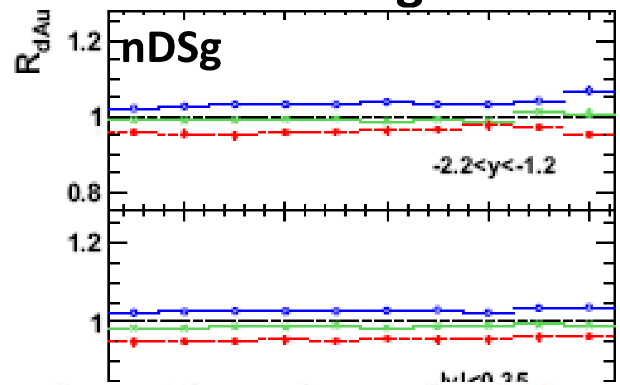


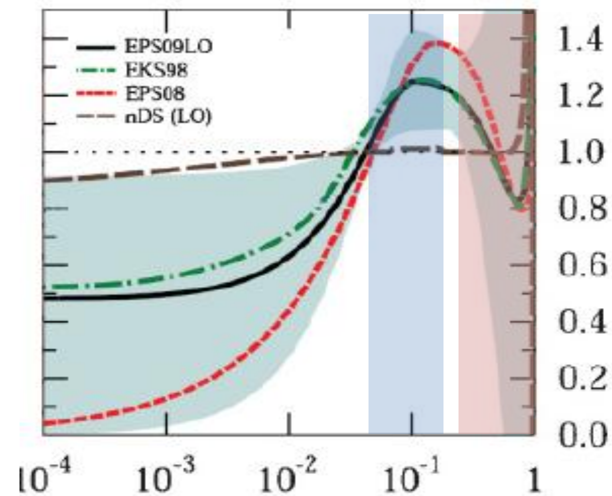
Work in progress: Υ transverse momentum dependence

Extrinsic scheme: σ_{abs}=0 mb, σ_{abs}= 0.5mb , σ_{abs}= 1 mb in 3 shadowing models









Growth of RdAu not related to Cronin effect:

it comes from the increase of x for increasing PT

$$x_\perp \propto \left(m^2_{J/\psi} + p^2_\perp\right)^{1/2}$$

- in the forward region: x goes **through the antishadowing** r

=> enhancement in R_{dAu}

- In the backward region: x **sits in an antishadowing and EMC** => decrease in R_{dAu}

Conclusions

- We have studied the influence of specific partonic kinematics

  within 2 schemes: intrinsic (2→ 1) and extrinsic (2→2) p_T
  for different shadowings: EKS98, EPS08, nDSg
  including nuclear absorption and different partonic models

- **CNM effects have to be taken into account as a baseline for a right interpretation of the J/Ψ as a QGP signal**

- **CNM effects depend on the partonic production mechanism**

- for J/ψ
  A+A collisi
  2 →2
  A+A collisi
  roduction

- for ϒ

  antishadowing and EMC region 2→2 process
  fractional energy loss in the forward region

http://phenix-france.in2p3.fr/software/jin/index.html